International Atomic Energy Agency

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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

PROCEEDINGS OF THE IAEA CONSULTANTS' MEETING

ON

DATA REQUIREMENTS FOR MEDICAL RADIOISOTOPE PRODUCTION

in co-operation with the
Institute of Physical and Chemical Research (RIKEN)

Tokyo, Japan, 20-24 April 1987

Edited by

K. Okamoto

January 1988

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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FOREWORD

The IAEA Nuclear Data Section is currently engaged in two projects related to medical applications, namely "Nuclear and Atomic Data for Radiotherapy" and "Nuclear Data for Medical Radioisotopes Production". These two programmes have obtained many favourable comments and have received encouragement for the further development of nuclear techniques in medical diagnostics and radiotherapy.

Several meetings, such as the International Symposia on Radiopharmaceutical Chemistry, the Symposia on Medical Applications of Cyclotrons and others, have been held which gave limited coverage to the topic of medical radioisotope production. But none of them has included data requirements systematically and explicitly.

In view of the stringent nuclear data requirements for the efficient production of radioisotopes, and because of the significant developments in the production of medical radioisotopes and their extensive use in the world, the IAEA Nuclear Data Section, with endorsement by the International Nuclear Data Committee (INDC) at its last meeting in June 1986, and in co-operation with the Institute of Physical and Chemical Research (RIKEN), as host, held a Consultants' Meeting on Data Requirements for Medical Radioisotope Production during the week 20-24 April 1987 in Tokyo. Twenty-three participants including twelve invitees from ten IAEA Member States, attended the meeting.

The objectives of the meeting were to:

1. Produce a survey of the medical radioisotope (RI) in use and their production methods.

2. Optimize the production methods:

   - recommendation of suitable nuclear reaction(s) and optimum energy range(s) production;
   - calculation of the expected production yields;
   - estimation of level radioactive impurities.

3. List reliable and generally available computer codes suitable for the calculation of excitation functions of radioisotopes, and describe their present status and limitations. Identify experimental gaps which can only be closed by theoretical calculations.

4. Develop guidelines and priorities for the compilation of available excitation functions including a list of scientists to be contacted.

5. Prepare an outline of the planned IAEA Handbook/Computer File for "Data for Medical Radioisotope Production" (list of contents, authors, etc).

6. Review the standard monitor reactions for the production of radioisotopes for medical use.

7. Enquire into the availability of appropriate target material (most time should be devoted to accelerator produced RI and only a short time for reactor produced RI).

All participants were requested before and during the meeting to emphasize nuclear data requirements in their presentations.

The proceedings contain the review papers, contributed papers presented at the meeting as well as the introduction and summary by the Chairman (S.M. Qaim). Also included are the summary, conclusions and recommendations of the following three Working Groups:

Working Group I:	Experiment and measurement of RI production Chairman: R.M. Lambrecht and S.L. Waters
Working Group II:	Calculation of computer file of excitation functions Chairman: M. Blann
Working Group III:	Data compilation (including the proposal of an IAEA Handbook on Data for Medical RI Production) Chairman: D. Berenyi

As scientific secretary of the meeting, I wish to express my gratitude and appreciation to RIKEN for their kind arrangement in hosting the meeting and for their special financial support for accommodation during the participants' stay in expensive Tokyo.

K. Okamoto
Editor
Scientific Secretary of the Meeting
IAEA Nuclear Data Section

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OPENING ADDRESS

by

Professor T. Miyazima
President of RIKEN

at the IAEA Consultants' Meeting on
"Data Requirements for Medical Radioisotope Production"

As President of RIKEN Institute which plays the role of host Institute of this IAEA Consultants' Meeting, I would like to extend our hearty welcome to all the participants who have come long ways to Japan.

First of all, let me explain how our Institute is adequate to host this meeting. Our institute was founded in 1917 with the purpose of promoting comprehensive basic research in science and technology which is indispensable in order to establish in Japan her own industry based upon her own discovery in science and technology. Here by comprehensive basic research I mean such research work that is done by collaboration of specialists of different research areas. The research area of our institute covers very wide range, namely nuclear physics, solid state physics, inorganic and organic chemistry, biological physics and chemistry, microbiology, basic engineering and basic medicine. This wide area in basic science and technology allows us always to be ready to meet any problems which are interdisciplinary in most cases and appear very often in real environment of science and industry.

Our institute is known by the construction of the first cyclotron in Japan in 1937 by the late Dr. Y. Nishina. Dr. Nishina is also famous by the theoretical work, the famous Nishina-Klein formula of photon-electron scattering. Since that time RIKEN has been one of the pioneers in areas covering not only fundamental nuclear studies but also more practical areas including radioisotope production, activation analysis and so on. The so called "baby cyclotron" invented by Dr. Karasawa is used in hospitals in order to produce short-lived isotopes for medical use. The automatic chemical system for making useful medical compounds from short-lived isotopes is another example of devices developed in our institute.

In 1980 the construction of a linear accelerator for heavy ions was completed, followed by the building of the largest SSC (separate sector cyclotron) which was completed in January this year. We expect that this cyclotron will be useful, not only for nuclear physics but also for extensive application in science and technology. We would like to welcome scientists from every corner of the world who wish to use this machine.

Generally speaking the doors of our institute are widely open for mutual collaboration and exchange to other institutes and universities of any nations under adequate conditions. When you visit our institute, you will find many visiting scientists are working whose number is comparable with the staff members of the institute.

Our cooperation with the IAEA this time started when Dr. Koichi Okamoto asked us to join the IAEA nuclear data network system in April 1983. After consulting with leading scientists of Japan in this field we decided participation in this international project. At the Expert Meeting held in Moscow in the same year, Dr. Hashizume of Riken represented us and since that time our contact with the organization has become closer. There is no need to mention the importance of international cooperation in peaceful use of science and technology. In this respect, the contribution of the IAEA is significant. Allow me to add that I myself has been a member of IFRC of the IAEA.

Lastly I wish to express gratitude to Dr. Okamoto of the Nuclear Data Section for his kind assistance given in connection with this Tokyo Meeting.

Hoping success of this Meeting, I thank you for your attention.

RIKEN; Institute of Physical and Chemical Research,
Wako, Saitama 351-01 Japan

Introductory Remarks

S.M. Qaim (Chairman)

Nuclear data relevant to medically important radioisotopes are divided into two major groups: the decay data and nuclear reaction cross section data. The decay data are of prime importance in deciding upon the suitability of a radioisotope for medical application, and the reaction cross section data are of great significance regarding the production and radionuclidic quality control of the desired radioisotope. In general, the decay data are known with sufficient accuracies, but the reaction cross section data need more attention.

The production of a radioisotope in a nuclear reactor generally involves one or several of the following processes: (n,γ), (n,p), (n,α) and (n,fission). The cross section data for all such neutron induced processes are well known and well documented, mainly as a byproduct of nuclear energy programmes. The use of charged particles from an accelerator or a cyclotron, on the other hand, provides good opportunity to produce neutron deficient radioisotopes which are generally more versatile for diagnostic applications. Depending upon the type of accelerated particles available and the energy ranges covered by the various machines, a large number of nuclear processes can be applied for production purposes. The demands for nuclear reaction cross section data are therefore diverse and often depend upon the particular programme of a laboratory, especially the type of cyclotron available. Furthermore, if a new demand arises, it generally needs to be fulfilled within a relatively short time. On the other hand, except for some special cases where radionuclidic quality criteria are rather stringent, the accuracy demands on the data are not very high.

Around the world about 25 laboratories are engaged in the field of charged particle induced nuclear reaction cross section data relevant to radioisotope production: N. America (8), Europe (8), Japan (4), Others (5). The experimental investigations cover different mass regions (from light mass β^+ emitters to therapeutic isotopes of At and Bi) and energy ranges (from 10 MeV minicyclotrons to 800 MeV accelerators). Furthermore, a few isolated groups are also engaged in compilation of excitation functions and thick target yields, as well as in developing calculational tools for predicting unknown cross sections. A critical appaisal of

nuclear data relevant to radioisotope production was initiated at Jülich [cf. 1,2] and the subject was also considered by the IAEA at the Consultants' level in 1981 [3]. Realizing the increasing demands in recent years on the compilation, evaluation and above all, standardization of charged particle induced reaction cross section data, the IAEA is convening the present Meeting. The main objectives are to survey the status of available nuclear data for medical radioisotope production, to identify the gaps in the data (if any), to discuss the experimental and theoretical methods of data acquisition and to give recommendations for removing the deficiencies and improving the quality of data. The programme includes both formal presentations and working group discussions. I expect that the deliberations will be critical, stimulating and fruitful, and will reflect a true cross section of the contemporary thoughts in this field of study.

[1] G. Stöcklin and S.M. Qaim: "Recent trends in nuclear reaction data needs for nuclear medicine", Proc. Int. Conf. on Neutron Physics and Nuclear Data for Reactors and other applied Purposes, Harwell 1978, OECD-NEA Paris, 667-687 (1979).

[2] S.M. Qaim: "Nuclear data relevant to cyclotron produced short-lived medical radioisotopes" Radiochimica Acta 30, 147-162 (1982).

[3] Summary Report of the IAEA Consultants' Meeting on Nuclear Data for Medical Radioisotope Production, Vienna (1981) INDC(NDS)-123/G+ (edited by K. Okamoto).

SUMMARY OF THE MEETING

S.M. Qaim (Chairman)

The Meeting was held in two parts. In the first part 19 review and contributed papers dealing with various aspects of medical radioisotope production were presented. The topics covered included survey of available experimental data, nuclear model calculations, radiation dose calculations, monitor reactions for beam intensity measurements, common and newer production routes (using mainly small, medium-sized and high energy cyclotrons, but also to some extent spallation and photonuclear reactions), and regional programmes. The second part of the Meeting consisted of informal and detailed discussions in three Working Groups, covering experimental data, nuclear model calculations and data compilations. The texts of formal presentations as well as the conclusions and recommendations arising from the working group discussions are given separately in these Proceedings. This summary therefore focusses only on some of the salient features of the Meeting.

About 50 radioisotopes are potentially important for medical applications, but only about 15 of them find routine application. It was agreed that the major attention should be directed towards those radioisotopes. Furthermore, only accelerator produced radioisotopes were considered.

The importance of decay data in relation to the radiation dose calculations and of reaction cross section data with regard to the optimization of production methods (especially the control of radionuclidic impurities) was underlined. It was, however, pointed out that the role of nuclear data in production process should not be over-emphasized. Targetry problems, characterization of chemical species formed during irradiations, specific activity of the product, etc. often demand more effort than nuclear data measurement. It was therefore suggested that nuclear data measurement programmes should be reviewed in the light of the utility of the radioisotope under investigation. Whenever possible measurements should be done in consultation with the users of the radioisotope.

The status of monitor reactions used for beam intensity measurements was critically reviewed. It was unanimously agreed that there is lack of uniformity in the use of standard reactions and that many of the discrepancies found in the reported cross section data may be attributed to this effect. The Consultants identified several reactions which are commonly used for monitoring p, d, ^{3}He and ^{4}He beams in various energy regions (cf. report of WG I). The IAEA was asked to arrange for an evaluation of those reactions on top priority basis so that recommended set of cross section values be made available to experimentalists.

There was considerable discussion on the standardization of measurements and reporting of data. It was strongly felt that many of the publications do not give enough experimental details so that the origin of a discrepancy is hard to trace. It is urged that the experimentalists give sufficient details on their measurements (sample

characteristics, monitor reaction and reference for its cross section, primary and calculated energies, detector efficiency calibrating standards, sources of errors, etc.). It would be very beneficial if the editors of relevant journals would encourage the authors reporting cross section data to follow the recommendations of this Meeting.

The status of available data was reviewed. The decay data are generally good, and only a few deficiencies were reported. Experimental information available on the cross section data for the production of routinely used radioisotopes (^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl etc.) via most common routes is also sufficient. There is however, a lack of agreed set of cross section values. A critical evaluation of the existing data was therefore deemed most essential.

Besides the production of routinely used radioisotopes, in larger laboratories some research work is constantly underway on the development of newer routes of production of established radioisotopes as well as on the investigation of new radioisotopes. In such cases there is often need of cross section measurements. In general those needs depend on the laboratory programme and regional constraints (type of cyclotron, energies of accelerated particles, availability of target material, etc.). During the Meeting some of the needs were identified (cf. report of WG I). It was emphasized that with increasing projectile energy the impurity problems become severe. For a stringent control of radionuclidic purity a strong data base is needed. The data needs also vary with developing technology. If a relatively rare process has been found to be technologically feasible, the demand for accurate data emerges rapidly.

Relatively little effort has been devoted so far to the compilation of nuclear data for medical radioisotope production, and that too was mostly based on individual initiatives. The Consultants encouraged the IAEA to follow this activity.

Considering the broad span of energies encountered in the field of medical radioisotope production (from ~ 10 MeV to ~ 800 MeV) and the fact that the accuracy requirements in nuclear data needs are in general not very high, it was felt that nuclear model calculations can serve as a useful tool in predicting unknown cross sections. Many calculational codes are available and could be applied but, since the radiochemists working in this field are not experts in nuclear model calculations, it was stressed that the codes be made available in a simple and user oriented form. The IAEA was asked to organize the testing and availability of such codes.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

Working Group I: EXPERIMENTAL DATA

R.M. Lambrecht (Chairman), S.L. Waters (Co-chairman), Lu Hanlin, S.M. Qaim, H. Umezawa, G.J. Beyer, H. Heinzl, M. Bonardi, T. Nozaki, A. Hashizume, M.C. Lagunas-Solar, K. Kitao, D. Berényi

The standardization of reported nuclear data for medical radioisotope (MRI) production could serve to, (i) establish and maintain international uniformity; (ii) improve the accuracy, where this would become necessary; and (iii) help developing laboratories and hospital- based medical cyclotron facilities. It was felt that there is a need to standardize the following parameters

- The type of particle accelerator and the incident beam energy and resolution set by the magnetic field or as measured by either time of-flight (neutron and/or gamma flash) or monitor reactions should always be reported.

  It was concluded that monitor reactions would be the most convenient and important to the largest number of laboratories involved in MRI production. The errors in incident energy, energy degradation in the target and the estimated error in stopping power should be cited.

- The following monitor reactions are very useful for beam energy and intensity measurements. These reactions were chosen on the basis of reported cross sections, decay properties of product nuclei and the suitability of target materials as monitor foils.

$^{12}C(p,pn)^{11}C$
$^{27}Al(p,3pn)^{24}Na$
$^{27}Al(p,3p3n)^{22}Na$
$^{59}Co(p,pn)^{58}Co$
$^{63}Cu(p,n)^{63}Zn$
$^{63}Cu(p,2n)^{62}Zn$
$^{65}Cu(p,n)^{65}Zn$
$^{nat}Cu(p,x)^{61}Cu$
$^{27}Al(d,3p2n)^{24}Na$
$^{51}V(d,2n)^{51}Cr$
$^{56}Fe(d,n)^{57}Co$
$^{nat}Ti(^{3}He,x)^{48}V$
$^{63}Cu(^{3}He,p3n)^{62}Zn$
$^{65}Cu(^{3}He,2n)^{66}Ga$
$^{65}Cu(^{3}He,p2n)^{65}Zn$

$^{27}Al(^{4}He,4p3n)^{24}Na$
$^{63}Cu(^{4}He,n)^{66}Ga$
$^{63}Cu(^{4}He,pn)^{65}Zn$
$^{65}Cu(^{4}He,2n)^{67}Ga$

- It was recognized that there is no general agreement on the use of standard reactions for monitoring beam energy and intensities and that this may be responsible for some of the discrepancies in the reported cross section data. It was strongly recommended that the IAEA make arrangements at the Agency or at another nuclear data center to compile and evaluate the data for the above reactions as soon as possible.

- All (reference) standard sources of radioactivities used for the calibration of detectors should be traceable to the IAEA or other reference laboratories recognized by the IAEA.

- The consultants were in unanimous agreement that all experimental data should be reported to journals and nuclear data banks in the form of cross-sections. A period of tolerance for the barn (for example until 1990) would be acceptable before the complete imposition of SI units.

- The topic of how to report practical thick target yields was more controversial. This has remained so since the publication and discussion summary of Svoboda and Silvester at the Oxford meeting in 1969(1). For the moment the selection of the practical unit (in terms of the way the data are to be used) should remain at the discretion of the author, although there was a strong focus toward the adoption of SI units. Reporting of the integral yield or production yield curve at saturation vs energy was considered useful to the MRI radiochemists.

- The working group asks the IAEA to communicate to experimentalists and editors of journals that publications should provide relevant experimental details about target preparation, including details of target composition, chemical form, isotopic abundance, preparation and containment and the estimation of the number of target atoms. Information about recoil range distribution, and beam power density effects on targets should also be described.

- Cross-section data for several medical radioisotopes are well documented. However, with increasing energy the data needs also increase. Many existing data are adequate, but in some cases more experimental measurements are needed. Due to the fact that each institution is in a different situation as regards the maximum particle energy available at a given accelerator, the types of the particles accelerated, the chemical form and enrichment of the target, only individual data needs could be identified. It was recognized that there are deficiencies in excitation functions

(1) Amphlett, C.B. (ed.), The Uses of Cyclotrons in Chemistry, Metallurgy & Biology, Proc. Conf. held at St. Catherine's College, Oxford, 22-23 Sept. 1969, Butterworth, London, 1970. Also K. Svoboda and D.J. Silvester presented their paper "Quantities and Unit Used in the Production of Radionuclides by Charged Particle Bombardment" to Int. J. Appl. Radiat. Isotopes 22 (1971) 269.

for a number of medical radioisotopes. It is believed that work is in progress in some laboratories on some of these reactions.

$^{11}B(p,n)^{11}C$
$^{13}C(p,n)^{13}N$
$^{38}Ar(p,n)^{38}K$
$^{40}Ar(p,3n)^{38}K$
$^{77}Se(p,n)^{77}Br$
$^{82}Kr(p,2n)^{81m+g}Rb$
$^{nat}Rb(p,xn)^{82}Sr$
$^{92}Mo(p,n)^{92}Tc$
$^{100}Mo(p,2n)^{99m}Tc$
$^{112}Cd(p,2n)^{111}In$
$^{123}Te(p,n)^{123}I$
$^{124}Xe(p,2p)^{123}I$
$^{124}Xe(p,pn)^{123}Xe$
$^{124}Xe(p,2n)^{123}Cs$
$^{74}Se(d,n)^{75}Br$
$^{82,83,84}Kr(d,xn)^{81}Rb$
$^{nat}Rb(d,xn)^{82}Sr$
$^{82,83,84}Kr(^{3}He,xn)^{82}Sr$
$^{82,83,84}Kr(^{4}He,xn)^{82}Sr$

- The consultants concluded that it would be useful if the IAEA in collaboration with other nuclear data centers would look criticially at the experimental information available on cross-sections and production yields for the more commonly used medical radioisotopes. These include ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl.

- The decay data for medical radioisotopes are in most cases well known and documented. However, during the meeting several radioisotopes were identified for which minor revision or verification of the available decay data would be desirable. These are ^{55}Co (half-life uncertainty), ^{52m}Mn, ^{77}Br, ^{62}Zn, ^{63}Zn, ^{66}Ga, ^{75}Kr, ^{77}Kr, ^{81m}Rb, ^{123}Xe, $^{195m+g}Hg$ - ^{195m}Au (branching ratios, γ-ray abundances, etc.). The IAEA is asked to bring these deficiencies to the attention of the relevant bodies.

- The working group encouraged the development of a compilation of nuclear data for medical radioisotopes produced by accelerators such as that independently initiated in 1981 by Qaim[2] and recently updated by NDS[3]. The working group proposed that

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(2) S.M. Qaim, Radiochimica Acta 30 (1982) 147-162

(3) D. Gandarias-Cruz and K. Okamoto, presented at this meeting "Nuclear Data for Medical Radioisotopes Produced by Accelerators - Status and Compilation".

the compilation should include all medical radioisotopes of current interest, and exhaustive references of all reported cross-section and production yield related details. A suggestion is to include threshold energies and thick target yields and to add the following radionuclides to the list prepared by NDS[3].

^{47}Ca, ^{67}Cu, ^{66}Ga, ^{75}Se, ^{77}Kr, ^{79}Kr, ^{89}Zr, ^{95m}Tc, ^{96}Tc, ^{100}Pd, ^{101m}Rh, ^{107}Cd-^{107m}Ag, ^{124}I, ^{157}Dy, ^{117m}Sn, ^{127}Xe, ^{169}Yb, ^{186}Re, ^{211}Rn- ^{211}At, ^{205}Bi, ^{206}Bi.

- The working group strongly supported the continuation of various IAEA activities in medical radioisotope production. The Agency should look at the matter at some intervals at the Consultants' level. Further more it was felt that a joint seminar dealing with nuclear data, technological and radiochemical aspects of accelerator radioisotope production (possibly in collaboration with the nuclear data, chemistry and physics sections of the Agency) be held around 1989.

- The question of enriched stable isotopes for medical radioisotope production was addressed by the Agency's Consultants' Meeting held in Turku in 1985[4]. This working group agrees that there are presently no serious difficulties in obtaining the commonly used highly enriched target materials for the production of ^{11}C, ^{13}N, ^{15}O, ^{18}F and ^{201}Tl. However, certain highly enriched stable isotopes required for medical radioisotope research and development are not readily available, e.g. ^{122}Te, ^{123}Te, ^{124}Xe.

- The working group recognized the predictive value of computer codes based upon nuclear models. It was, however, strongly emphasized that the codes should be user oriented, and that the Agency should encourage access to these codes.

- A wide distribution of this report by the IAEA is strongly recommended, (a detailed list of recipients will be augmented by the working group).

Conclusions

The Consultants' working group on experimental data recommended the following actions on the part of the Agency. (1) The compilation and evaluation of data for nuclear reactions used to monitor accelerator beam energy and intensity as soon as possible, (2) the evaluation of cross sections and production yields for the commonly used accelerator produced medical radioisotopes, (3) the transmission of deficiencies in certain excitation functions and nuclear data to the relevant bodies, (4) the compilation of nuclear data for all accelerator produced medical radioisotopes, (5) the holding of a seminar on nuclear data, technological and radiochemical aspects of medical radioisotope production around 1989, and (7) the dissemination of the results of the discussion on the standardization of the cross-section measurements to experimentalists, journal editors, and libraries.

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(4) Summary Report of the IAEA Consultants' Meeting on "Cyclotron Production of Radionuclides with Enriched Targets", Turku, Finland, 22-25 July 1985 (edited by H. Vera-Ruiz).

Working Group II:

CALCULATION AND COMPUTER FILE OF EXCITATION FUNCTIONS

M. Blann (Chairman), A. Pavlik, K. Hata, M.C. Lagunas-Solar
S.M. Qaim, K. Sueki

SUMMARY

We have heard a well balanced and versatile range of presentations spanning the range of accelerator production of radioisotopes for medical applications. Here we wish to say a few words about the presentations dealing with nuclear model codes as a tool for use in radioisotope production.

There was unanimous agreement that the final answer in obtaining necessary reaction cross sections, if feasible, should always be experimental. Yet, we also saw in many of the research end of the field the wish to understand reaction cross sections in terms of nuclear reaction models, and perhaps eventually to be able to use these models as a guide in selecting the best experimental conditions for producing a given radioisotope without having to measure all the possible reactions.

Along these lines we heard preliminary efforts by Lagunas-Solar in interpeting his yields of F-18 with ALICE code. Lu Hanlin and his co-workers at Beijing have the most impressive agreement with the experimental excitation functions around A=87 region using a code they wrote based on the hybrid precompound and Weisskopf-Ewing evaporation models. We hope to get more information on this fine code.

The RIKEN workers, given in the papers by Tendow, Kitao and Sueki, have also illustrated the comparisons of calculated excitation functions with several data sets. The question was raised as to whether the calculations may sometimes not be of a help to select the better data set when there are large disagreements between several sets.

A major step beyond the usual statistical/precompound codes was presented by Hata of JAERI in the OSCAR code. This is really a code system designed to give the thick target yield information necessary to most medical radioisotope production problems. It includes the use of experimental thin target yields as input when available, supplemented by results from systematics from the ALICE nuclear model code where experimental results are not available. A contribution from Masumoto suggests algorithms for computing yields for photonuclear reactions.

There were two additional papers stressing the use of nuclear theory. Pavlik gave a summary of physics of several of the popularly used codes. He went on to illustrate the excellent results which could be obtained by careful applications of STAPRE (Hauser-Feshbach plus exciton model) code of Uhl. The latter is internationally recognized as the best code in the class. Pavlik showed predictive power to within 30% of experimental yield. We hasten to point out that experimental yields may often have systematic errors approaching this limit.

Blann presented comparisons of the results of ALICE code with a broad range of nuclear reactions, mostly proton and light ion induced, at energies up to 200 MeV. The calculated results shown were generally done by the experimental groups who measured the relevant excitation functions. The philosophy of ALICE code (Weiskopf-Ewing plus hybrid model) differs from that of STAPRE, in that it is not intended to give the best possible calculation, but rather it stresses ease of use by non-experts, and short computer time requirements. There is agreement between the Vienna and Livermore code groups that STAPRE is the code of choice when the highest possible accuracy (30% region) is desired, and ALICE is useful when a factor of two or better is adequate, and when the user wishes to keep the investment in time to run the codes at a minimum.

Some conference participants felt that the capability of running model codes in their laboratories would be valuable. With many codes in existence, the IAEA could help in the selection of process by summarizing important facts on the availability and capability of each code. Working Group II has prepared specific recommendations in this regard.

RECOMMENDATIONS

The working group feels that computational capability of excitation functions is a valuable tool to help guide ultimate experimental programs in radioisotope production for medical applications.

The IAEA or a related organization could provide a very valuable service to this community in several ways, the goal being to aid in the selection and determination of availability of these codes.

In order to evaluate the suitability of the many codes in existence, and to efficiently select the code or codes best fitting each laboratory's needs, a compilation of answers to a few questions would provide a valuable service. An initial set of questions is as follows:

(1) What codes are presently available which are suitable for general use for calculating excitation functions, and to whom does one write to receive a copy of these codes? Is there any cost? Are the codes written entirely in for example, a standard FORTRAN language?

(2) For each code available, is there a manual or some documentation explaining how to run the code?

(3) Are sample input and output available for checking the operation of the code on the end user's computer? What are the options on input and output?

(4) What physics is in the code - e.g. Wiesskopf or Hauser Feshbach, type of precompound decay; are γ-ray cascades treated?

(5) What is the maximum excitation energy which the distributed version of the code will accommodate?

(6) What is the range of $\Delta A$and ΔZ of product nuclei (i.e. how many neutrons and protons may be emitted in a single calculation?

(7) Are all reaction paths treated in a 'single pass', or are multiple passes required?

(8) What projectiles may be accommodated in the entrance channel and in the exit channel?

(9) Are discrete levels allowed in the input? Are they required?

(10) How are level densities handled?

(11) Give a sample input for some test problem.

(12) What is the computer core requirement and running time on the author's computer? Is the code known to run on any smaller computer?

(13) Is the code written to run in batch mode or in interactive mode?

A second valuable result to present would be an intercomparison of several of these codes in calculating several excitation functions. Recommended are the $^{127}I(p,xn)$ and $^{75}As(p,xn)$ excitation functions at incident proton energies up to 70 MeV. It would be nice to have the sample input for each code required to run these tests, and the computer type and CPU time used. These calculations should be performed for incident protons in 2 MeV energy increments. Results of all calculated excitation functions should be shown graphically, together with the experimental results on the same graphs.

A resonably complete list of codes/authors/users was sent from Livermore (M. Blann) as follows:

STAPRE (IRK)	S. Wilboolsak, B. Strohmaier, M. Uhl, Vienna
STAPRE (LLL-1)	D.G. Gardner, M.A. Gardner, LLNL, Livermore
GNASH (LAS)	P.G. Young, LANL (N.B.- there are several) GNASH- HF, WE, Los Alamos
EMPIRE (IBJ)	M. Herman, ENEA, Bologna; A. Marcinkowski, Warsaw University, Warsaw
PERINNI (ECN-1)	H. Gruppelaar, H.A.J. van der Kamp, Petten
HAUSER-V (TRM-1)	S.B. Garg, A. Sinha, BARC, Trombay Bombay
TNG (ORL)	C.Y. Fu, ORNL, Oakridge
PRANG (ECN-2)	H. Gruppelaar, H.A.J. van der Kamp, Petten No γ-ray competition included (future option: see GRYPHON code, Ref. H. Gruppelaar, I.M. Akkerman, Int. Conf. on Nuclear data for Basic and Applied Science, Santa Fé, USA, May 1985 and Rep. ECN 164)
PEOGM (SLO)	E. Bevtak, Bratislava
GNASH (JAE)	K. Shibata, E. Arthur, P.G. Young, Tokai, LANL
PREM(TOH)	G. Keeni, S. Yoshida, Sendai
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These exercises are intended to inform the medical radioisotope producer community as to which codes are available to them, and which are compatible with their specific needs and computational resources. The second part is intended to show the relative merit of the output of these codes, which is an important criterion in deciding which code or codes to implement.

Working Group III: DATA COMPILATION

(including Proposal for an IAEA Handbook on
"Data for Medical Radioisotope Production"

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The Working Group III held its session in the form of a plenary meeting and discussed the issue of the compilation of the most important nuclear data for the medical radioisotope production by accelerators and that of a proposed IAEA Handbook on Nuclear Data for Medical Radioisotope Production.

After some discussion it was concluded that it is not timely and suitable to publish a compilation and a handbook separately.

It is suggested to make one publication with the title "Handbook on nuclear data for medical radioisotope production". The contents could be as follows: In a short introduction the most important nuclear concepts on radioisotope production by accelerators should be clarified (in a "definition-like" way). Then comes a section with evaluated cross section data for the production of some of the most important medical radioisotopes (e.g. the lightest positron emitting isotopes for PET studies, namely ^{11}C, ^{13}N, ^{15}O, and ^{18}F and other isotopes such as ^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl) as well as those for monitor reactions. In this section the rules for standardization of the pertinent data should also be included (see the Report of WG1) which would be guide-line for the evaluators but - at the same time - it might promote to measure and publish the data concerned by the authors in the future in a more unified and more complete way. It is also expected that the evaluation work on the data for production of most important medical radioisotopes will show the shortages and inconsistencies in the pertaining data and so it can initiate further experimental studies in some cases.

Finally, an important part of the handbook would be a rather detailed and somewhat critical tabulation (a compilation) of the data for the production of medical radioisotopes (see some details in the Report of WG1).

SESSION I

GENERAL

MEDICAL RADIOISOTOPES AND NUCLEAR DATA

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Abstract

A brief review of some of the medically important radioisotopes is given. The significance of reaction cross-section data in optimising production methods is dicussed. The most common routes of production, the useful energy ranges and the status of cross-section data are described. Some recent trends in production methods and data needs are outlined.

INTRODUCTION

A radioisotope finds application in nuclear medicine only if it meets certain criteria. Those criteria relate to the physical, chemical and biochemical properties of the radioisotope, especially of the biomolecule labelled with the radioisotope. In general there are five guiding principles in the choice and use of a radiopharmaceutical:

- Minimum radiation dose
- Suitable radiation and high resolution scans
- High specific activity
- Organ specificity
- Availability

The first two considerations deal with the physical properties of the radioisotope and the characteristics of the radiation detection system used. A short-lived radioisotope having γ-rays in the energy region of 60 to 300 KeV is preferred. If it emits a predominant or single γ-ray, it is of greater advantage since single photon emission computed tomography (SPECT) can be performed. Similarly β^+ emitters are also of great significance since three dimensional high resolution scans can be obtained via positron emission tomography (PET). Some of the radioisotopes find therapeutic applications, especially if they emit α- or high energy β^--particles, or Auger electrons.

Specific activity and organ specificity are the major criteria in the choice of a radiopharmaceutical for performing metabolic studies. The function of the radioisotope is simply to allow in-vivo detection of the pharmaceutical. Since a greater part of modern diagnostic nuclear medicine deals with metabolic studies rather than simple imaging, the choice lies mainly on radioisotopes which form good covalent bonds with the biomolecules.

The availability of a radioisotope at the place of application is an important factor regarding its widespread use. Many of the short-lived radioisotopes are available only near the site of production (using either a reactor or a cyclotron). A different approach making use of a long-lived parent from which a short-lived daughter can be periodically milked off (termed as a generator system) has also been very successfully applied. In such systems both reactor and cyclotron produced parent activities have been used.

MEDICAL RADIOISOTOPES

On the basis of various considerations described above, the number of radioisotopes which have been found useful or appear to be potentially useful for medical applications amounts to about 50. Several review articles, monographs and books dealing with them have been written [cf. refs. 1-7]. In general all of the radioisotopes can be classified tentatively [cf. 8] in the following seven groups:

1. "Organic" short-lived β^+ emitters (^{11}C, ^{13}N, ^{15}O, ^{18}F etc.)
2. Halogens (^{18}F, $^{75,77}Br$, ^{123}I etc.)
3. Rare gases (^{77}Kr, ^{133}Xe etc.)

4. Generator systems (^{68}Ge-^{68}Ga, ^{82}Sr-^{82}Rb, ^{99}Mo-^{99m}Tc etc.)
5. Alkali and alkali like metals (^{38}K, ^{82}Rb, ^{201}Tl etc.)
6. "Inorganic" radionuclides (^{52}Fe, ^{67}Ga etc.)
7. Therapeutic radionuclides (^{77}Br, ^{125}I, ^{211}At etc.)

Some of the commonly used radioisotopes, with their major decay properties and areas of application, are given in Table I. The list of potentially useful inorganic radioisotopes is large. However, those radioisotopes would find application mainly as organometallic complexes and considerable chemical efforts would be required to obtain the desired compounds. In Table I therefore only a few typical inorganic radioisotopes are given.

NUCLEAR DATA

Significance of Cross-Section Data

As discussed above the decay data of a radioisotope constitute one of the major criteria for its use in nuclear medicine. The reaction cross-section data, on the other hand, determine its availability in a suitable quantity and purity. A detailed discussion of the importance of nuclear data is given elsewhere [cf. 5, 8]. It should be emphasized here that cross-section data are needed as a function of projectile energy for

- estimating thick target yield of the radioisotope to be produced
- determining the energy range optimum for its production.

Thick target yield

The yield of a radioisotope expected from a particular thickness of the target (thick target yield) can be calculated by an

TABLE I. SOME COMMONLY USED MEDICAL RADIOISOTOPES

RADIOISOTOPE	DECAY DATA [A]			MAJOR APPLICATION
	$T_{1/2}$	MODE OF DECAY	PRINCIPAL γ-RAYS KEV (% ABUNDANCE)	
^{11}C	20.3 MIN	β^+(99.8), EC(0.2)		FUNCTIONAL IMAGING USING PET AGENTS
^{13}N	10.0 MIN	β^+(100)		—— " ——
^{15}O	2.0 MIN	β^+(99.9), EC(0.1)		—— " ——
^{18}F	110 MIN	β^+(96.9), EC(3.1)		—— " ——
^{30}P	2.5 MIN	β^+(100)		—— " ——
^{38}K	7.6 MIN	β^+(100)		MYOCARDIAL PERFUSION USING PET
^{43}K	22.2 H	β^+(100)	373(70), 618(80)	MYOCARDIAL PERFUSION
^{51}Cr	27.7 D	EC(100)	320(10.2)	RED BLOOD CELL SURVIVAL; BLOOD VOLUME
^{52}Fe	8.3 H	β^+(56.5), EC(43.5)	169(99.2)	HEMATOLOGY
^{67}Ga	78.3 H	EC(100)	93(38), 185(24)	TUMOR LOCALISATION
^{68}Ga [B]	68 MIN	β^+(90), EC(10)		BLOOD BRAIN BARRIER USING PET
^{75}Br	1.6 H	β^+(75.5), EC(24.5)	286(92)	FUNCTIONAL IMAGING USING PET AGENTS
^{77}Br	57.0 H	β^+(0.7), EC(99.3)	239(23), 521(22)	VARIOUS PHARMACEUTICALS; THERAPY [C]
^{77}Kr	1.2 H	β^+(79.8), EC(20.2)	130(87), 147(41)	CEREBRAL BLOOD FLOW USING PET
^{81m}Kr [B]	13 S	IT(100)	191(67)	LUNG VENTILATION; PERFUSION
^{82}Rb [B]	1.3 MIN	β^+(96), EC(4)	776(15.5)	MYOCARDIAL PERFUSION USING PET
^{97}Ru	2.9 D	EC(100)	216(86)	KIDNEY FUNCTION
^{99m}Tc [B]	6.0 H	IT(100)	142(89)	FUNCTIONAL IMAGING USING SPECT AGENTS
^{111}In	2.8 D	EC(100)	172(88), 245(94)	TUMOR LOCALISATION
^{123}I	13.0 H	EC(100)	159(83)	FUNCTIONAL IMAGING USING SPECT AGENTS
^{125}I	60.0 D	EC(100)	35(6.7)	RADIOIMMUNOASSAY; THERAPY [C]
^{131}I	8.0 D	β^-(100)	364(81)	THYROID THERAPY [D]
^{133}Xe	5.3 D	β^-(100)	81(37)	CEREBRAL BLOOD FLOW; LUNG VENTILATION
^{195m}Au [B]	31 S	IT(100)	262(67)	FIRST PASS ANGIOGRAPHY
^{201}Tl	73.5 H	EC(100)	166(10.2)	MYOCARDIAL PERFUSION
^{211}At	7.2 H	Ec(58) α(42)	687(0.2)	THERAPY [E]

A) DECAY DATA GENERALLY TAKEN FROM TABLE OF ISOTOPES, 7TH EDITION, EDITED BY C.M. LEDERER AND V.S. SHIRLEY, JOHN WILEY, NEW YORK (1978).
B) THIS IS A GENERATOR NUCLIDE MILKED OFF PERIODICALLY FROM THE RESPECTIVE LONG-LIVED PARENT.
C) VIA AUGER ELECTRONS D) VIA β^--PARTICLES E) VIA α-PARTICLES

integration of an experimentally determined or theoretically estimated excitation function over the energy range covered by the target. The calculated yield, however, represents the maximum yield which can be expected via a given nuclear process. In practice, the experimentally obtained yields in high current production runs are invariably lower than the theoretical values. As an example the experimental yield of ^{123}I from the $^{124}Te(p,2n)^{123}I$ process using a 99 % enriched $^{124}TeO_2$ target is shown in Fig. 1 [cf. 9]. The experimental yield decreases as a function of the

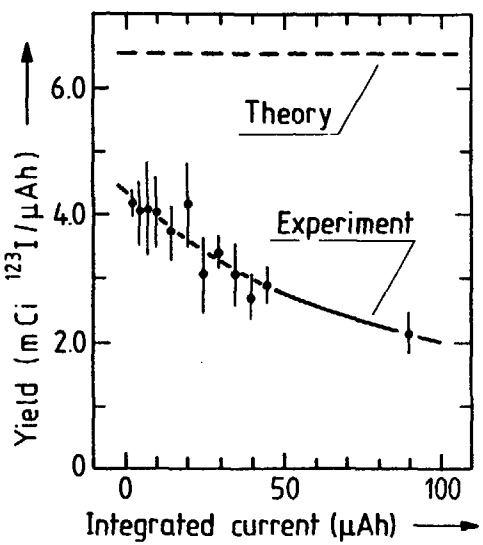

Fig. 1: Experimental yields of ^{123}I (mCi/μAh) for a 99.97 % enriched $^{124}TeO_2$ target of thickness E_p = 22.4 → 20.0 MeV as a function of the integrated current [ref. 9]. Theoretical values obtained from the excitation function given in [ref. 13].

integrated current, presumably due to inhomogeneity in the incident beam, radiation damage effects, loss of the product as a result of high power density effective at the target, etc. [cf. 9, 10]. This is all the more so if a liquid or gaseous target is used. The difference between the experimental and theoretical yields generally increases with the increasing current of the projectiles and the thickness of the target [cf. 11]. It is therefore emphasized that a yield value calculated from the excitation function should in no case be extrapolated to high current production conditions.

Some users tend to hold the view that full information on the excitation function of the nuclear reaction used for the production of an isotope is not necessary and that only experimental thick target yield data are sufficient. This approach may be more practical but it remains empirical since the experimental yield reflects only the specific conditions prevalent during the production process. An accurate knowledge of the excitation function, and therefrom the theoretical thick target yield, helps in designing target systems capable of giving optimum yields.

Optimum energy range

A selection of the projectile energy range that will maximize the yield of the desired product and minimize that of radioactive impurities is of vital importance in optimizing a production method. Whereas the non-isotopic impurities produced are removed by chemical separation, the level of isotopic impurities is difficult to control. Such radioactive impurities have a dual effect: firstly, they affect the line spread function adversely (resulting in bad resolution of the scintiscans [cf. refs. 12]) and secondly, cause enhanced radiation dose to the patient. If the amount of a longer-lived impurity is too high, it may jeopardise the whole advantage of the short-lived radioisotope used. The level of impurities can be suppressed by using enriched isotopes as target materials and, more importantly, by a careful selection of the particle energy range effective in the target. The latter demands an accurate knowledge of the excitation functions of the various competing reactions.

The production of ^{123}I ($T_{1/2}$ = 13.0 h) and ^{75}Br ($T_{1/2}$ = 1.6 h) via (p,2n) reactions on highly enriched ^{124}Te and ^{76}Se, respective-

ly, provide good examples of the importance of nuclear data [cf. 13, 14]. Fig. 2 shows the excitation functions of (p,xn) reactions on 96.5 % enriched ^{76}Se. Due to competition between $^{76}Se(p,n)^{76}Br$ and $^{76}Se(p,2n)^{75}Br$ reactions it is not possible to eliminate ^{76}Br ($T_{1/2}$ = 16.0 h) from ^{75}Br completely, even if ^{76}Se would be 100 % enriched. The optimum energy for the production of ^{75}Br at a compact cyclotron is E_p = 24 → 21.5 MeV, i.e., the energy of the incident protons should be selected as 24 MeV and the thickness of the selenium target should degrade the energy only to 21.5 MeV. The level of ^{76}Br-impurity in this energy range is expected to be ~ 2 %.

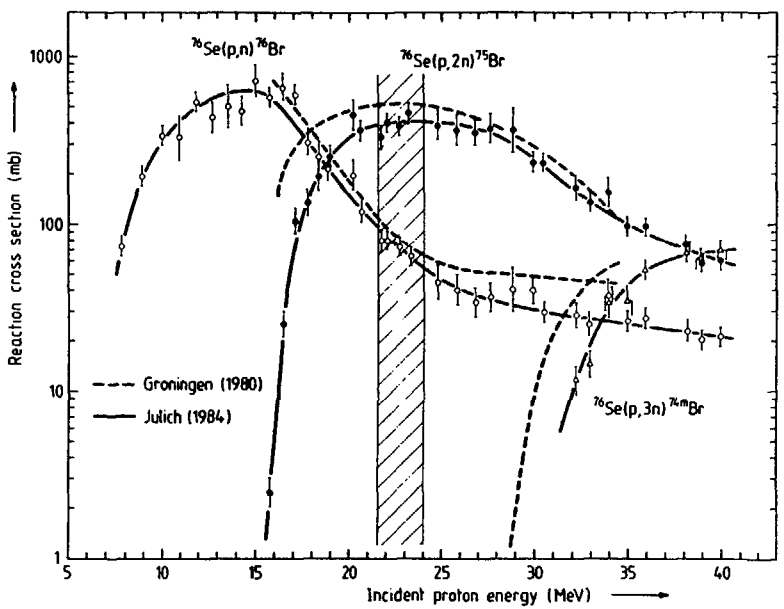

Fig. 2: Excitation functions of (p,xn) reactions on 96.5 % enriched ^{76}Se [cf. ref. 14].

It should be pointed out that at low projectile energies the number of open reaction channels is generally small but with increasing incident particle energies several competing reactions set in. Thus the impurity problem is more severe if high energy nuclear reactions are used for production purposes.

Production Routes

A radioisotope may be formed via several nuclear processes and cross-section data for all the reactions may be desired. It should, however, be emphasized that not every reaction is suitable for large scale production. Apart from the cross-section data, such considerations as the available energy of the projectiles, ease of target construction, capability of withstanding high beam currents as well as the subsequent chemical processing have to be taken into account. The production of ^{18}F constitutes a somewhat typical example. The radioisotope can be produced in a no-carrier added form via five major processe, viz. $^{16}O(^3He,p)^{18}F$, $^{16}O(\alpha,d)^{18}F$, $^{18}O(p,n)^{18}F$, $^{20}Ne(d,\alpha)^{18}F$ and $^{20}Ne(^3He, p)^{18}F$ [for a recent review cf. 15]. The thick target yields calculated from the reported excitation functions are given in Fig. 3. For large scale production, however, the $^{18}O(p,n)^{18}F$ and $^{20}Ne(d,\alpha)^{18}F$ processes are preferred

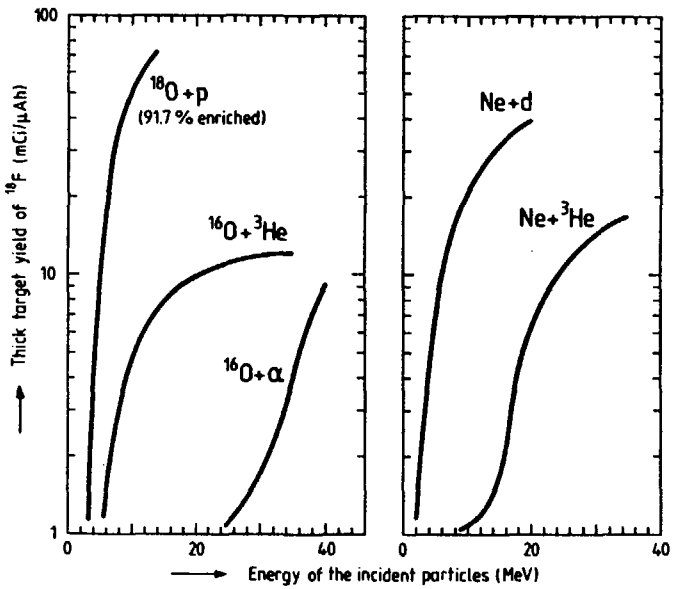

Fig. 3: Theoretical thick target yields of ^{18}F expected from various reactions on oxygen and neon isotopes [cf. ref. 15].

TABLE II. COMMON PRODUCTION ROUTES FOR SOME MEDICAL RADIOISOTOPES

RADIOISOTOPE	NUCLEAR PROCESS	ENERGY RANGE (MEV)	STATUS OF CROSS-SECTION DATA AND COMMENTS
^{11}C	$^{14}N(p,\alpha)^{11}C$	16 → 4	GOOD, EVALUATION NEEDED
	$^{10}B(d,n)^{11}C$	10 → 0	FAIR, —— " ——
^{13}N	$^{12}C(d,n)^{13}N$	8 → 0	FAIR, —— " ——
	$^{16}O(p,\alpha)^{13}N$	16 → 4	FAIR, —— " ——
^{15}O	$^{14}N(d,n)^{15}O$	8 → 0	GOOD, —— " ——
^{18}F	$^{20}Ne(d,\alpha)^{18}F$	15 → 3	GOOD, —— " ——
	$^{18}O(p,n)^{18}F$ A)	16 → 3	FAIR, SINGLE MEASUREMENT
^{30}P	$^{27}Al(\alpha,n)^{30}P$	28 → 10	GOOD
^{38}K	$^{35}Cl(\alpha,n)^{38}K$	28 → 10	POOR
^{43}K	$^{40}Ar(\alpha,p)^{43}K$	35 → 12	FAIR
	$^{nat}V(p,spall)^{43}K$	590.800	FAIR
^{51}Cr	$^{50}Cr(n,\gamma)^{51}Cr$ B)	n_{th}	GOOD
	$^{51}V(d,2n)^{51}Cr$	30 → 5	GOOD
^{52}Fe	$^{nat}Cr(^3He,xn)^{52}Fe$	45 → 10	FAIR
	$^{nat}Ni(p,spall)^{52}Fe$	450.800	FAIR
^{67}Ga	$^{68}Zn(p,2n)^{67}Ga$ A)	30 → 15	FAIR
$^{68}Ge(^{68}Ga)$	$Rb,Br(p,spall)^{68}Ge$	500.800	FAIR
^{75}Br	$^{76}Se(p,2n)^{75}Br$ A)	28 → 20	GOOD
	$^{75}As(^3He,3n)^{75}Br$	36 → 25	GOOD
^{77}Br	$^{75}As(\alpha,2n)^{77}Br$	28 → 14	GOOD
	$^{nat}Mo(p,spall)^{77}Br$	800	FAIR
^{77}Kr	$^{nat}Br(p,xn)^{77}Kr$	40 → 25	GOOD
	$^{77}Se(^3He,3n)^{77}Kr$ A)	36 → 25	GOOD
$^{81}Rb(^{81m}Kr)$	$^{82}Kr(p,2n)^{81}Rb$ A)	23 → 15	POOR
$^{82}Sr(^{82}Rb)$	$^{nat}Mo(p,spall)^{82}Sr$	800	FAIR
^{97}Ru	$^{nat}Mo(^3He,xn)^{97}Ru$	36 → 12	GOOD
$^{99}Mo(^{99m}Tc)$	$^{nat}Mo(n,\gamma)^{99}Mo$	n_{th}	GOOD
	$^{235}U(n,f)^{99}Mo$	n_{th}	GOOD
^{111}In	$^{111}Cd(p,n)^{111}In$ A)	15 → 4	FAIR
	$^{109}Ag(\alpha,2n)^{111}In$	30 → 15	GOOD
^{123}I	$^{124}Te(p,2n)^{123}I$ A)	26 → 21	GOOD, EVALUATION NEEDED
	$^{127}I(p,5n)^{123}Xe \rightarrow ^{123}I$	65 → 50	GOOD, —— " ——
	$^{124}Xe(p,x)^{123}Xe \rightarrow ^{123}I$ A)	30 → 25	POOR
^{125}I	$^{nat}Xe(n,\gamma)^{125}Xe \rightarrow ^{125}I$	n_{th}	GOOD
^{131}I	$^{nat}Te(n,\gamma)^{131}Te \rightarrow ^{131}I$	n_{th}	GOOD
^{133}Xe	$^{nat}Xe(n,\gamma)^{133}Xe$	n_{th}	GOOD
	$^{235}U(n,f)^{133}Xe$	n_{th}	GOOD
$^{195m}Hg(^{195m}Au)$	$^{197}Au(p,3n)^{195m}Hg$	34 → 26	FAIR
^{201}Tl	$^{nat}Tl(p,xn)^{201}Pb \rightarrow ^{201}Tl$	30 → 20	GOOD, EVALUATION NEEDED
^{211}At	$^{209}Bi(\alpha,2n)^{211}At$	45 → 20	GOOD

A) USING HIGHLY ENRICHED ISOTOPE AS TARGET MATERIAL.
B) SPECIFIC ACTIVITY ENHANCED VIA SZILARD-CHALMER'S PROCESS.

since both of them can be used at a low energy cyclotron and since target technology has been developed in both the cases - in the former process a small-sized $H_2{}^{18}O$ target is used and in the latter a high-pressure Ne gas target.

An exceptional example is provided by the production of the more widely used ^{123}I. Although about 25 nuclear reactions have been suggested, only three processes, namely $^{124}Te(p,2n)^{123}I$, $^{127}I(p,5n)^{123}Xe \rightarrow ^{123}I$ and $^{124}Xe(p,x)^{123}Xe \rightarrow ^{123}I$, have found major application.

The most common production methods for the medically important radioisotopes (listed in Table I) are described in Table II. The energy ranges used are also given. For more comprehensive lists encompassing all the useful or potentially useful nuclear reactions other reviews should be consulted [cf. 1-8, 15-17].

Status of Cross-Section Data

The status of cross-section data (according to the judgement of this author) for the nuclear processes used is given in Table II. In a few cases some comments are also added. The references to the original literature are to be found in some compilations [cf. 18-20] and review articles [cf. 5, 8, 15-17].

Two of the very widely used radioisotopes in nuclear medicine, viz. ^{99m}Tc and ^{125}I, are produced in a nuclear reactor. Similarly ^{51}Cr, ^{131}I and ^{133}Xe are also produced in a reactor. The cross-section data of the processes involved are well known. In all of the other cases a cyclotron or an accelerator is used. Whereas the short-lived β^+emitters can be produced using small-sized cyclotrons, the production of most of the other important radioisotopes demands a medium-sized cyclotron accelerating several particles (p,d,^3He ^4He). In some cases high energy accelerators with facilities for irradiations in parasitic positions have proved to be advantageous. The status of data for reactions induced in various energy regions therefore varies considerably. The available data for the production of the commonly used radioisotopes (short-lived β^+ emitters, ^{123}I, ^{201}Tl etc) are generally good. In each case a critical evaluation of the data is, however, needed.

Recent Trends in Production and Data Needs

In recent years small-sized cyclotrons have experienced a renaissance. There has been a strong tendency to use single particle minicyclotrons ($E_p \leq 11$ MeV) and two particle Baby Cyclotrons ($E_p \leq 17$ MeV, $E_d \leq 10$ MeV) for the production of short-lived β^+ emitters. The latter machines are more versatile and lead to higher yields. Efforts have also been underway to use single particle medium-sized cyclotrons ($E_p \leq 40$ MeV) for the production of several important radioisotopes like ^{123}I, ^{201}Tl etc. The optimum use of those machines demands investigation of newer routes of production, often involving highly enriched isotopes as target materials. Whereas in the case of a small-sized cyclotron the (p,n) process is the most promising reaction, at a 40 MeV cyclotron (p,2n), (p,pn) and (p,3n) processes are more probable.

The excitation function of the $^{15}N(p,n)^{15}O$ reaction, which constitutes an alternative route for the production of ^{15}O at a small cyclotron, was recently remeasured at Brookhaven [cf. 21] and is reproduced in Fig. 4. The calculated thick target yield is

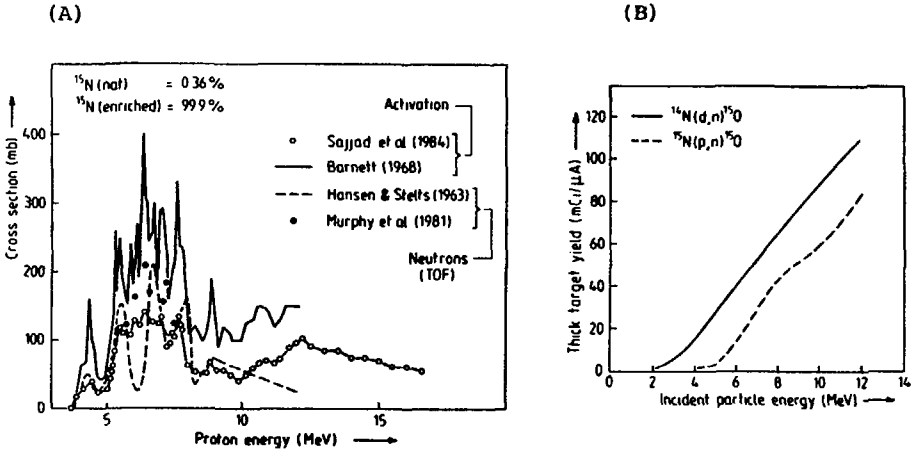

Fig. 4: (A) Excitation function of the $^{15}N(p,n)^{15}O$ reaction on 99.9 % enriched ^{15}N measured by the activation and neutron time-of-flight techniques [21].
(B) Thick target yields of ^{15}O from the commonly used $^{14}N(d,n)^{15}O$ reaction and the alternative process $^{15}N(p,n)^{15}O$ [ref. 21].

also given. It is smaller than that from the commonly used $^{14}N(d,n)^{15}O$ reaction but is sufficient for application. Target design may pose some problem since highly enriched ^{15}N is needed and a normal flow system would be too expensive. Detailed and precise cross-section measurements are needed for several other cases like $^{11}B(p,n)^{11}C$, $^{13}C(p,n)^{13}N$, $^{77}Se(p,n)^{77}Br$, $^{123}Te(p,n)^{123}I$ etc.

A recently developed method for the production of ^{123}I makes use of highly enriched ^{124}Xe as target material. The method in-

volving $^{124}Xe(p,2n)^{123}Cs \rightarrow ^{123}Xe$ and $^{124}Xe(p,pn)^{123}Xe$ processes for the production of $^{123}Xe \rightarrow ^{123}I$ precursor system is technically well advanced, although the question of nuclear data has not been addressed in detail. An accurate measurement of the excitation function would help optimise the conditions of production.

Despite these newer trends, the production of many of the important radioisotopes is continuing at medium-energy cyclotrons accelerating various charged particles. Some of the examples include the ^{3}He-particle induced reactions for the production of ^{52}Fe, ^{75}Br, ^{77}Kr, ^{97}Ru etc. and α-particle induced reactions for the formation of ^{30}P, ^{38}K, ^{77}Br etc. Similarly the spallation process at high energy accelerators, especially for the production of two very important generator systems (^{68}Ge-^{68}Ga and ^{82}Sr-^{82}Rb), is of great utility. Obviously search for newer routes of production will continue in all the directions.

In general it may be said that the nuclear data needs relevant to radioisotope production are difficult to predict. Furthermore, if a need arises it has to be fulfilled within a relatively short time. The data measurement programme should therefore run in close association with the other technical development work.

Acknowledgement

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Status of Nuclear Data for Internal Absorbed Radiation Dose Calculations

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ABSTRACT

Areas of concern are: (1) MIRD calculations, (2) the standardization of short-lived positron emitters for positron emission tomography (PET) instrumentation and calibration of radioisotope dose calibrators, and (3) microdosimetry, i.e. energy deposition by low-energy internal conversion and Auger electrons, beta and alpha particles at the cellular level.

Radiation Absorbed Dose Estimates are readily calculated for the internally distributed radionuclides commonly used in medicine, by the MIRD method (1,2). The calculation requires:

1) determination of the amount of activity and time spent by the radioactivity in the source organ. This relates to pharmacokinetics rather than nuclear data (with the exception of radiation detector measurements).

2) calculation of the total amount of radiation emitted by the radioactivity in the source organ. This requires knowledge of the energy and abundance of all nuclear disintegrations.

3) determination of the fraction of energy emitted by the source organ that is absorbed by the target. This depends on the type and energy of emissions (absorption characteristics) and on the anatomic relationships between source and target. The nuclear decay for the common medical radioisotopes is sufficiently established so as to require only limited discussion at the present workshop.

The difinitions (2) and relevant nuclear data, absorbed fractions and mean dose per cumulative activity are tabulated and are readily available. Computer codes are readily available for performing the calculations for the usual radionuclides utilized in nuclear medicine. The nuclear decay for the common medical radioisotopes is sufficiently established so as not to require further discussion at the present workshop.

The standardization of short-lived positron emitters for calibration of positron emission tomography (PET) instrumentation and radioisotope calibrator calibration is an area of concern (3) that will be mentioned.

An important area of research (4) with respect to nuclear data relates to the energy deposition by low-energy internal conversion and Auger electrons, alpha and beta particles at the cellular level. This is important because (1) of damage to chromosomes induced by decay of diagnostic radiopharmaceuticals such as ^{111}In; (2) determination of the suitability of a radionuclide with nuclear emissions having a short range in tissue that are proposed as a label for radioimmunotherapeutic agents (i.e. monoclonal antibodies designed as specific carriers of radioactivity to cancerous cells). These topics are part of the focus of separate International Symposia being held in the near future (5).

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SESSION II

EXPERIMENTAL TECHNIQUES AND STATUS OF DATA

"Medical Radioisotope production in the UK with special reference to the experiences of using nuclear data sources"

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ABSTRACT

A short review is presented concerning the production of medically useful radiositopes in the UK. The various Nuclear Data Sources which are currently used to facilitate this production are cited and certain inadequacies in this literature are highlighted. In particular, the chemical effects in targets which influence radioisotope yields are discussed, and it is recommended that some data may require re-assessment bearing these effects in mind.

INTRODUCTION

This report will try to address in part most of the aims and objectives of the Consultant's meeting, from the view point of those researchers in the United Kingdom who are concerned with the process of medical radioisotope production. The centres contacted in the course of the writing of this report include groups producing materials using both reactors and accelerators, and in the following paragraphs and tables I have summarised the present production capabilities.

I have refrained from an indepth study of specific reactions but have instead concentrated on the use and the need for nuclear data by these groups.

For ease of presentation I have split the radioisotopes into two categories, those produced from reactors and those produced from charged particle induced reactions.

REACTOR PRODUCED RADIOISOTOPES

The principal producer of reactor radioisotopes in the U.K. is Amersham International, and Table One summarises their present catalogue of materials. A number of these items are brought in bulk from overseas whilst others are produced with the reactors at Harwell and processed on the Amersham site.

TABLE ONE

REACTOR PRODUCED MEDICAL RADIOISOTOPES AVAILABLE FROM AMERSHAM INTERNATIONAL

RADIOISOTOPE	HALF LIFE	TARGET MATERIAL	NUCLEAR REACTION
^{24}Na	15.02h	$NaCC_3$(Natural)	$^{23}Na(n,\gamma)^{24}Na$
^{32}P	14.3d	S (Natural)	$^{32}S(n,\gamma)\ ^{32}P$
^{35}S	87.4d	KCl (Natural)	$^{35}Cl(n,p)\ ^{35}S$
^{47}Ca	4.54d	$CaCO_3$(50% ^{46}Ca)	$^{46}Ca(n,\gamma)\ ^{47}Ca$
^{51}Cr	27.7d	Cr (94.6% ^{50}Cr)	$^{50}Cr(n,\gamma)\ ^{51}Cr$
^{58}Co	70.8d	Ni (Natural)	$^{58}Ni(n,p)\ ^{58}Co$
^{59}Fe	44.6d	Fe_2O_3(90% ^{58}Fe)	$^{58}Fe(n,\gamma)\ ^{59}Fe$
^{75}Se	119.8d	Se(99% ^{74}Se)	$^{74}Se(n,\gamma)\ ^{75}Se$
^{85}Sr	64.8d	$SrCO_3$(57% ^{84}Sr)	$^{84}Sr(n,\gamma)\ ^{85}Sr$
^{89}Sr	50.5d	$SrCO_3$(90% ^{88}Sr)	$^{88}Sr(n,\gamma)\ ^{89}Sr$
^{90}Y	64.1h	Y_2O_3 (Natural)	$^{89}Y\ (n,\gamma)\ ^{90}Y$
$^{99}Tc^m$	6.02h	Fission Product	$U(n,f)^{99}Mo \rightarrow {}^{99}Tc^m$
$^{113}In^m$	99.5m	Sn (80% ^{112}Sn)	$^{112}Sn(n,\gamma)^{113}Sn \rightarrow {}^{113}In^m$
^{125}I	60.0d	Xe (25% ^{124}Xe)	$^{124}Xe(n,\gamma)\ ^{125}Xe \rightarrow {}^{125}I$
^{131}I	8.04d	Te_2O_3 (Natural)	$^{130}Te(n,\gamma)\ ^{131}Te \rightarrow {}^{131}I$
^{133}Xe	5.25d	Fission Product	$U\ (n,f)\ ^{133}Xe$
^{137}Cs	30.17y	Fission Product	$U\ (n,f)\ ^{137}Cs$
^{192}Ir	74.0d	Ir (Natural)	$^{191}Ir\ (n,\gamma)^{192}Ir$
^{198}Au	2.70d	Au (Natural)	$^{197}Au\ (n,f)^{198}Au$

The neutron rich radioisotopes summarised in the above table are mostly of sufficient half-life to have well defined decay schemes, and the data appearing in "Nuclear Data Sheets" (Published by Academic Press. New York. USA) is more than adequate for this purpose. The problems in measuring the levels of radioactive contaminants is generally of little consequence, the data being readily available. Many targets are prepared using enriched sources bought in from TECHSNA EXPORT, Moscow, USSR, or OAK RIDGE NATIONAL LAB. Tenn., USA, and no problems of purity or supply have been reported.

All the methods summarised in Table One were established some years previously so that the present production data is only compared with this historic data. Cross-sectional data for these "routine" reactions are rarely consulted.

CHARGED PARTICLE INDUCED REACTIONS

There are many centres in the UK who are using accelerators for the production of medical radioisotopes and the nuclear data requirements for these radioisotopes fall into many categories. Two aspects are illustrated in the following tables. In Table Two there is a list of the present accelerator facilities in the UK. This list summarises the particles and energies available and gives a brief description of the principal programme of research at each centre.

TABLE TWO ACCELERATOR FACILITIES IN THE UK

CENTRE	TYPE OF ACCELERATOR	PARTICLES AVAILABLE	ENERGIES MeV	COMMENTS
ABERDEEN	CS-30 (TCC) (Ex,MRC Edinburgh)	Protons Deuterons Helium 3++ Helium 4++	26) Fixed 15) 38) 30)	Setting up to run an on-site PET programme
AMERSHAM	1 Philips	Protons	25 Fixed	Principally internal beams for commercial production
	2 CP-42 (TCC) -ve ion M/C	Protons	40 Fixed	
	3 MC-40 (Scanditronix)	Protons	40 Variable	
BIRMINGHAM	1 "NUFFIELD"	Protons Deutrons Helium 3++ Helium 4++	10) 20) Fixed 30) 40)	Internal and external beams
	2 "Radial Ridge"	Helium 3++	35	Physics type facility "tight" internal beam
HARWELL	"VEC"	Protons Deuterons Helium 3++ Helium 4++ Heavy ions	60 Variable 42 Energies 85 86	Experimental external beams
MRC				
1. CLATTERBRIDGE	MC 60 (Scanditronix)	Protons	60 Fixed	Neutron Therapy programme
2. HAMMERSMITH	MC 40 (II) (Scanditronix)	Protons Deuterons Helium 3++ Helium 4++	38 Variable 20 Energies 52 39	Research facility for on-site PET programme and isotope production.

The data presented in the following Table Three is a compilation of the accelerator produced radioisotopes which are presently available. It does not include those materials that have been produced in the past and which can be re-introduced if there is sufficient clinical demand, e.g. ^{13}N: ^{30}P: ^{62}Zn: $^{87}Y^{m}$: ^{89}Zr: ^{97}Ru: ^{157}Dy.

TABLE THREE ACCELERATOR PRODUCED RADIOISOTOPES

RADIOISOTOPE HALF-LIFE	LABORATORY	PRINCIPAL NUCLEAR REACTION	ENERGY WINDOW MeV	PRINCIPAL CONTAMINANTS	YIELD DATA COMPARISON
A. PET PROGRAMME					
^{11}C 20.4m	MRC/ABER	$^{14}N(p,^4He)$	15--4	(No ^{15}O)	Experimental data from BNL and Julich. (a)
^{15}O 2.03m	MRC/ABER	$^{14}N(d,n)$	6--0	(No ^{13}N)	
^{18}F 109.6m	MRC/ABER	$^{20}Ne(d,^4He)$	19--0		Experimental data reviewed in (b)
	MRC/ABER	$^{16}O(^3He,p+n)$	53--0	^{11}C+^7Be +Recoils	
	MRC/ABER	$^{16}O(^4He,d+2n)$	39--0	^7Be(?) + Recoils	

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B. RESEARCH/COMMERCIAL PRODUCTION

^{22}Na	2.6y	BIRM	$^{28}Mg(d,^4He)$	20 -- 0			
^{43}K	22.2h	MRC/BIRM	$^{40}Ar(^4He,p)$	18 -- 0	^{42}K + Recoils	MRC measurements	(c)
^{52}Fe	8.27h	MRC/BIRM	$^{Nat}Cr(^3He,xn)$	30 -- 0	^{55}Fe(<0.3% EOB)		(d)
		BIRM	$^{*50}Cr(^3He,xn)$	30 -- 0	^{55}Fe(<0.01%EOB)	Initial experiments	
^{55}Co	17.5h	BIRM	$^{*54}Fe(d,n)$	9 -- 0			

Table Three (cont/d)

^{57}Co	271d	AMER	$^{*58}Ni(p,pn+2p)$	25 -- ?	^{56}Co,^{58}Co	Inter comparisons	
^{67}Ga	78.3h	AMER	$^{*68}Zn(p,2n)$	25 -- ?	^{66}Ga,^{68}Ga		
^{67}Cu	61.9h	BIRM	$^{Nat}Ni(^4He,p)$	40 -- ?	?	Initial experiments	
^{77}Br	57.0h	MRC/BIRM	$^{75}As(^4He,2n)$	30 -- 0	^{76}Br <1% EOB	MRC measurements	(e)
		HAR	$^{79}Br(p,3n)^{77}Kr$	39 -- ?	No ^{76}Br	Comparison with exc. functions	(b)
^{81}Rb	4.58h	MRC/BIRM	$^{79}Br(^4He,2n)$	28 --20	$^{82}Rb^m$,^{83}Rb,^{84}Rb	MRC measurements +	(f)
		MRC	$^{Nat}Kr(p,xn)$	40 --20		Yield highly dependent	
		HAR	$^{Nat}Kr(p,xn)$	60 --40		on targetry	

* Enriched target material

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Table Three cont/d

^{111}In	2.81d	AMER	*$^{112}Cd(p,2n)$	25	-- ?	$^{114}In^{m}$	Inter comparisons
$^{114}In^{m}$	49.5d	BIRM	$^{Nat}Cd(d,xn)$	20	-- ?	?	Initial experiments
^{123}I	13.2h	HAR	$^{127}I(p,5n)^{123}Xe$	60	--45	^{125}I(<0.2%EOB)	Harwell measurements +(g,h)
^{124}I	4.15d	BIRM	$^{121}Sb(^{4}He,n)$	38	--10	^{125}I, ^{126}I	
$^{195}Hg^{m}$	40h	HAR	$^{197}Au(p,3n)$	34	--26		Harwell measurements (i)
^{201}Tl	73.1h	AMER	*$^{203}Tl(p,3n)^{201}Pb$	28	-- ?	^{200}Tl,^{202}Tl	Inter comparisons
^{203}Pb	51.9h	MRC/BIRM	$^{203}Tl(d,2n)$	15	-(~12)	$^{202}Pb^{m}$,$^{204}Pb^{m}$	
^{211}At	7.22h	HAR/BIRM	$^{209}Bi(^{4}He,2n)$	30	-- 0		(j)

* Enriched target material

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Experiences on the use of nuclear data sources for charged particle induced reactions.

Generally speaking any radioisotope destined to be produced by charged particle irradiation will be initially located using the "Chart of the Nuclides" (1) and the half-life and decay scheme checked against the "Table of Isotopes" (2). In cases where there is a significant discrepancy in this data then "Nuclear Data Sheets" will be consulted and on rare occasions the National Physical Laboratory will become involved in validating available data or remeasuring decay parameters. Such a study which was initiated by the clinical use of the $^{82}Sr/^{82}Rb$ generator, has just been published (3).

The production route chosen by each laboratory will depend on what irradiation facilities are available at any particular time. For instance, it may be possible to accelerate a ^{3}He beam but unless it is used routinely the practical problems of running the beam occasionally may outweigh any advantages that the ^{3}He route can offer. This may especially be the case if the economics of the situation are taken into account. In addition, there may be times when it would be more cost effective for a laboratory to "buy in" irradiated target materials which have been produced elsewhere, such as the longer lived materials ^{22}Na, ^{68}Ge, ^{82}Sr and ^{109}Cd.

If it is decided to use an on-site facility, a feasibility study if often undertaken and a research programme initiated to determine optimum targetry which maximise yields and minimise contaminants. Reaction Q values and thresholds are most likely to be examined at this first stage and these are generally calculated from mass excess values

appearing in the "Table of Isotopes" or taken directly from Maples, Goth and Cerny [4]. The choice of the energy window will often be critical in deciding to what extent contaminants will be present and a knowledge of the excitation function data is invaluable both qualitatively and quantitatively. However, the reaction routes used by other laboratories which appear both in the open literature and research reports, are probably the most influential data in helping to decide the exact irradiation parameters. Even though some accelerators have variable energy beams available, it is often the case that they perform most efficiently at preferred energies. Thus a good knowledge of range/energy data is always required especially to optimise the choice and thickness of the machine foil, target foil, target material, and back plate material. Most laboratories in the UK use the Williamson tables [5], for this purpose. The use of all the previously quoted literature sources are invaluable in optimising irradiation parameters but one extra very useful source of information used to identify impurities is the γ-ray catalogue. Three sources are in use at present with laboratories having their own preferences. [6, 7, 8]

Yield data comparisons

Yields for the various reactions which appear in Table Three have not been included for a variety of reasons, the most important being the difficulties with inter-comparisons. However, a knowledge of the excitation function is paramount in these deliberations and the compilations from Oak Ridge [9, 10] and Brookhaven National Laboratory [11] are useful in this respect, but the majority of laboratories by-pass these reports and go directly to the open literature. With so many variables affecting the final yield of a radioisotope from a charged particle irradiation, it is not surprising that no two laboratories agree on a common figure. That is not to say that laboratories do not make comparisons, but to make these worthwhile they have to be aware of the effects of all the variables on the final yield.

Many of these variables are chemical in nature and this is particularly true of gas targets and solid targets with gaseous products which are often irradiated under flow conditions with a number of different "carrier" gases. The composition of these carrier gases are often critical in obtaining any product from the target and can affect the chemical species of the recovered radioactive material. A review of some of these phenomenon can be found in Clark and Buckingham [12].

For example, the production of ^{15}O from the $^{14}N(d,n)^{15}O$ reaction at 16.1 MeV using a nitrogen gas target can provide $^{15}OO(O_2)$ or $C^{15}OO(CO_2)$, depending on whether 4% O_2 in N_2 or 2.5% CO_2 in N_2 is used as the sweep/target gas, and the radioactive yield of ^{15}O can vary by 20-30%. If little or no oxygen carrier is present in the target the recovered ^{15}O yield is greatly reduced as the principal chemical forms of the recovered gas are $N_2{}^{15}O$ (N_2O) and $N^{15}OO(NO_2)$ which are most reactive and interact with the target and transfer lines.

Other examples of similar effects can be found with the $^{20}Ne(d,^{4}He)^{18}F$ reaction, where a specific level of F_2 carrier is required to quantitatively recover ^{18}F from the target [13]. Similarly it has been reported that with the production of ^{81}Rb from the $^{nat}Kr(p,xn)\ ^{81}Rb$ reactions, a proportion of the alkali metal product remains in the gas phase after irradiation [14].

The additional effect of reduced gas density during irradiation has also been noted with gas targets. This is a most important aspect which needs to be appreciated when scaling up a feasibility study at low currents and short irradiation periods, to a production situation where higher current densities are necessary. Raising the target pressure in order to keep the gas target "thick" during irradiation can, however, result in many other problems for the recovery of the product [14].

Future requirements for sources of Nuclear Data

It has been shown in the previous paragraphs that the "background" data used in the measurement of excitation functions is reasonably well documented but it is generally agreed by those working in radioisotope production laboratories in the UK that a number of inadequacies still exist. For instance, there are no experimental cross-section data appearing in the literature for some specific reactions. I have not troubled to list these here as they will probably be appearing in other contributions to this meeting. Additionally, there may be some deficiencies in the "background" data for these reactions when they are studied in more detail. For example, anomolies in the decay scheme of a short-lived isomeric state may be important especially if the radioisotope contributes to the overall yield of the desired product. These problems will become more apparent as experimental work proceeds.

All the groups in the UK stressed the usefulness of using the most recent data sources which appear in the literature and it was generally felt that there should be an active encouragement for all experimentalists in the field to provide "good" data. One way this could be achieved would be to have drawn up internationally agreed guidelines for the experimental procedures used for excitation function measurements.

It is interesting to note that the majority of users of such data in the UK were trained as chemists and it would be hoped that any handbook/source file might be drawn up with this point in mind. Thus a knowledge of thin/thick target yields as well as the basic cross-section data would be highly desirable. It would also be of great value that when future compilations of excitation functions appear there could be some form of comment as to the reliability of the compiled data using the criteria layed down in the proposed guidelines. The precision in the data need not necessarily be to the nearest 0.1%, but to know that most (if not all) of the production parameters had been taken into consideration would give confidence in using the data predictively. Parameters such as beam energy, beam current, beam strike area, target thickness and target composition are fundamental to any yield measurement but it is no easy task to have complete assuredness of their values. The parameter which is often neglected because it is even more difficult to measure is the chemical effects in targets. As previously mentioned, this is particularly true of solid targets giving gaseous products and gas targets which give rise to reaction products that interact with the target walls. For it is these chemical effects which so often makes any yield comparison between what is "theoretically" possible and what is measured in the reaction flask so unpredictable.

SUMMARY

In this report I have attempted to survey the production of the medically important radioisotopes that are available from UK laboratories, and to highlight the present and future use for Nuclear Data Sources.

As far as the reactor-produced radioisotopes are concerned there hasn't been identified any specific need for an extension or revision of the nuclear data sources that are already available. However, the data for accelerator produced radioisotopes may have some inadequacies. In particular, there appears to be a requirement for a set of guidelines to help experimentalists with their measurements and for any listing of yield data to incorporate these criteria into the compilation.

There are also a number of specific reactions which may be of general interest, that have had little or no experimental work carried out on them. Perhaps this meeting will identify these reactions and recommend a systematic study to be undertaken.

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Monitor Reactions for the Production of Radioisotopes for Medical Use

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ABSTRACT

In obtaining integral cross sections of a nuclear reactions by foil activation method, the accuracy of the results are affected by many factors. One method to minimize some of these systematic errors is to measure relatively the cross sections comparing to a monitor reaction cross sections in place to measure absolutely. The use of the monitor reactions have also advantage when the set up of Faraday cup is difficult as in the case of internal beam.

The $^{12}C(p,np)^{11}C$ reaction is a well known standard for proton induced reactions. The experimental errors of cross sections are distributed from 3 to 7 percent which depend on incident energies. Other reactions such as $^{27}Al(p,3pn)^{24}Na$, $^{63}Cu(p,2n)^{62}Zn$, $^{65}Cu(p,pn)^{64}Cu$ have been used for the monitor reactions in the measurement of excitation function. For deutron induced reactions, $^{27}Al(d,x)^{24}Na$ has been employed. For alpha induced reactions, the $^{27}Al(\alpha,x)^{24}Na$ has been used. The present status of these monitor reactions were surveyed and possibility of developing new monitor reactions are discussed.

1. Needs of monitor reaction

To produce known quantities of radioisotopes for medical use, the yields of concerned reaction is one of important factors. Though the yield curve can be obtained from the experiment, the choice of the best condition of a bombardment, such as incident beam energy and target thickness can be calculated also by integrating the cross section of nuclear reactions. This procedure is important to estimate the maximum production condition with minimum inpurities. As the errors of a yield curve are amplified from the errors of the cross sections by integrating process, it is necessary to obtain the accurate values of cross sections.

Though there are many factors which cause errors in obtaining experimentally the cross sections, one of important systematic errors comes from the estimate of a beam flux. The beam flux is usually obtained by measuring the electric currents induced by incident beam in a Faraday cup. However, if a precaution is not made for the escape of electrons or ions which will be caused by secondary elecrons or ionization of gas due to insufficient vaccum etc., the measurement of beam intensities may cause an error unexpected. This error of beam intensities affects of cause the final value of cross section systematically.

Instead to measure the cross sections each time absolutely, it is more easier to measure the cross sections relative to those of a monitor reaction whose cross sections in the interested energy region is already knwon. The use of monitor reaction have also advantage where Faraday cup for beam flux monitoring is difficult to use in case of internal beam of high energy accelerators.

Protons are most extensively used for the production of radioisotopes. And for the monitor reaction, the $^{12}C(p,pn)^{11}C$ reaction has been an object of precise measuremnt of cross section.[1] In the early stage of development of high energy proton accelerators, the $^{12}C(p,pn)^{12}C$ reactions were used as a monitor. This reaction has the threshold of 18.5 MeV, and nearly 100 % positron decay was convenient for the determination of activity ald also because of its short half-life(20.5 m), activation and counting times can make short. However, other reactions are often used for a monitor reaction when one measure the cross sections of which reaction products are useful for medical applications. One reason is that the $^{12}C(p,pn)^{11}C$ reaction has relatively high threshold. Other reason is that one can now measure the intensities of γ-rays much easier and convenienty with a germanium detector. And additional reason is that aluminum or cupper is very accesible material for the target. Table 1 shows the kinds of monitor reactions together with references of the employed users. The energy regions studied and quoted errors by the authors were also shown.

2. The condition for monitor reactions

Idealy, the monitor reaction should satisfy the follwing conditions.

1) The elements should be isotopically pure or disturbances of quantitative determination of reaction product caused by other isotope products are small.

2) The absolute cross sections should be known precisely in wide range of energies of incident particles.

3) The cross sections should change smoothly as incident particle energies increase. The reaction which have sharp resonance should be avoided.

4) The cross sections to other reaction channels should be small.

5) The effects of secondary particles induced by primary reactions should be small.

6) The half-life of reaction product should not to be too short or very long as compaired to irradiation time.

7) The target foil should be obtained without difficulty.

8) The target should be stable during the irradiation. The elements which have low melting point shoud be avoided.

9) The reaction products should be remain in the target materieal. If the reaction products are rare gas, the products would be escape from the target and this will cause large error in the determination of cross sections.

10) The activity of reaction products can be determined accurately and easily. The emitting probability of detecting radiation should be accurately known.

The monitor reactions to be commonly used for a probon beam are $^{12}C(p,pn)^{11}C$, $Al(p,x)^{24}Na$, $^{63}Cu(p,n)^{63}Zn$, $^{65}Cu(p,n)^{65}Zn$. The data for these reaction were compiled and compared for each reaction.

3. $^{12}C(p,pn)^{11}C$ reaction

There is no ideal reaction which fulfill all above conditions even proton induced reactions. However, there is a good reason that the $^{12}C(p,pn)$ is selected for primary monitor reaction. This reaction fulfill the above requirements, (1), (2), (3), (4), (5), (7), and (8).

Since the review by Cumming[1], several authors reports concerning this reaction (ref. (2), (3), (4), (5) and (6)). Measday[24] have measured the cross section from 50.7 to 158.6 MeV obtaining good agreement (85.2 3.0 mb at 50.7 MeV) with the resut by Cumming[7] (86.4 2.6 mb at 50.5 MeV). Table 2 summarizes the values of cross section reported by digital values Figure 1 and 2 show the situation from about 20 MeV to 800 GeV.

4. $^{27}Al(p,x)^{24}Na$ reaction

The present status is shown in Fig. 3. As shown in the figure, large descrepancies are observed between the results of different experiments from threshold to about 70 MeV. And even at 80 MeV, the error pronounced by each experiment is too small to cover the differences between different experiments. One reason could be attributed to the energy estimates which were very degraded by targets and absorbers from high incident energy. The recent values of Michael et al.[26] are come from relative values obtained to that of $^{27}Al(p,x)^{22}Na$. Above 100 MeV, the agreement of Michael's and Hick's results are good, though Hick's value are systematically smaller than Michael's values. The results of Holub show a pronounced sharp peak at 65 MeV. It is not clear if the energy resolution of experiments by Holbus is better than the other experiments, because neither beam condition nor target thickness is explicitly given.

5. The $^{63}Cu(p,n)^{63}Zn$ and $^{65}Cu(p,n)^{65}Zn$ reactions

As the threshold of $^{63}Cu(p,n)^{63}Zn$ and $^{65}Cu(p,n)^{65}Zn$ reactions are 4.21 and 2.17 MeV respectively, these reactions are used to monitor the beam intensity in lower energy region than

$^{11}C(p,pn)$ or $Al(p,x)^{24}Na$ reactions. The proton induced reactions with copper target has been also the subject of theoretical investigations and many authors studied this reaction. Table 3 and 4 show reaction lists for these reactions.

$^{63}Cu(p,n)^{63}Zn$ reaction: The data of 14 experiments were plotted in Fig. 4. This reaction was investigated since 1950. In this early stage, the activity was determined by counting positrons with GM counters. Their emitting probability in the decay employed in the investigation were 89.3 or 90% in comparison to the value of 93 %(evaluated value of R.L.Auble in Nuclear Data Sheets, 28,559(1979) which is now commonly adopted. So the small correction should be made for the effect of different decay scheme. In the figure the plots were not corrected to show the difference of original data. The results of Meadow [7] and Ghoshal[50] are shifted higher values. The data of Albert[53] and Chacket[57] is also about 35 % higher than Collé's[6] data at 9.3 MeV. The accord of Collé's and Grutter's[3] results which are the most recent precise measurements is good.

Yoshizawa's results which were taken by using ISOL were interpreted as $^{63}Cu(p,n)$ and not $^{nat}Cu(p,n)$, because by this interpretation, the data is reasonably normalized to Meadow's results at 25 MeV as explained by the authors. However the difference between Grutter's and Yoshizawa's results are apparent. One needs more measurement above 22 MeV.

$^{65}Cu(p,n)^{65}Zn$: The 17 experiemntal results were plotted in Fig. 5. One also observe the shift to higher value for the experiments wich have done in the period from 1950 to the begining of 1960(Howe[52], Chackett[57], Humes[58], Williams[66]). The agreemens of the data of Collé[6], Kopacky[70] and Grütter[3] are good, though there is systematic trend that Grutter's results is smaller than Kopacky's. The data of Green[72] and Gadioli[68] are larger than those of data of Colle's or Grutter's results. Above 20 MeV, more experiment is requested.

6. Conclusion

As shown in table 3 many reactions have been used for the beam monitor. In the proton induced reactions, the data of cross section of the $^{12}C(p,pn)^{11}C$ have good precision in wide energy region. However as indicated, even in $^{63}Cu(p,n)^{63}Zn$ and $^{65}Cu(p,n)^{65}Zn$ reactions for which many studies have been made, there exist some discrepancies which may not be solved clearly. And also, for the different kinds of incident beam than protons, it seems the experimental precision is not sufficient in all interested energy regions. So it is necessary to make mo precise experiments for the monitor reactions.

For the evaluation of the cross sections, one also have to reprsents experimental results with those of theoretical calculations. In the above 4 reactions examined, the theoretical curves have not yet succeeded to agree with experimental data in considerable range of energies. Effort also should be made in this direction.

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Table 1. Monitor reaction List used for the measurement of cross sections of the reactions useful for medical use.

Kind of reaction	Authors and Reference	Energy region	Errors of cross section	Ref. of used reaction
$^{12}C(p,pn)^{11}C$	*	21-300 GeV	0.6-4.7	(14)
$Al(p,x)^{7}Be$	Heydegger(2)	118-800 MeV	15	(15)
	Grutter (3)	540,593	3.5	
$Al(p,x)^{22}Na$	Heydegger(2)	82-800	10	(15)
	Grutter (3)	540,593	3.6	
$Al(p,x)^{24}Na$	**	70-190	9-14	(16) (17)
$^{63}Cu(p,n)^{63}Zn$	Colle (6)	3 MeV-11.5 GeV	3-11	(18) (19)
$^{63}Cu(p,2n)^{62}Zn$	Greene (4)	16-33 MeV	10	(19) (20)
$^{65}Cu(p,n)^{65}Zn$	Colle (6)	3-100	3-11	(21)
$^{65}Cu(p,pn)^{64}Cu$	Newton (5)	23-102	5.9	(20)
$^{65}Cu(p,4n)^{62}Zn$	Meadows (7)	34-100	not reported	(20)
$^{27}Al(d,p\alpha)^{24}Na$	Lenk (8)	11-28	2	(21)
	Martens (9)			(19)
$^{51}V(d,2n)^{51}Cr$	Weinreich(10)	5-90	6-12	(22)
$^{56}Fe(^{3}He,p2n)^{56}Co$	Hazan (11)	18-29	25	(19)
$^{56}Fe(^{3}He,pn)^{57}Co$	Hazan (11)	6-29	20	(19)
$^{56}Fe(^{3}He,2n)^{57}Ni$	Hazan (11)	6-29	20	(19)
$^{nat}Ti(^{3}He,X)^{48}V$	Weinreich(10)	5-130	6-12	(21) (23)
$^{27}Al(\alpha,2p)^{29}Al$	Probst (12)	15-152	8-15	(21)
$^{27}Al(\alpha,^{7}Be)^{24}Na$	Martens (13)	40-103	2.5	(19)

* See table 2
** Refer to the references in Fig. 3.

Table 2 Integral cross sections of the $^{12}C(p,pn)^{11}C$ reaction

E_p			Comments	Author	Ref.
20.7 MeV	38.0	3.0	Targets 10mg/cm^2 polyethylene well scintillator, 12% gas loss correction	Cumming	(25)
21.1	32.9	1.1			
30.1	89.1	3.0			
33.5	92.5	3.1			
37.7	90.0	3.0			
42.0	89.4	3.0			
42.8	91.0	3.0			
44.2	88.8	3.0			
50.5	86.4	2.6			
32.0	49.4	3.9	1.75 mg/cm^2,CH_2	Aamodt	(26)
50.7	85.2	3.0	1.4 mm thick CH, the incident proton energy were degraded by carbon absorbers NaI scinti gas loss is less than 1.1 %.	Measday	(24)
59.5	80.3	2.8			
64.7	80.6	2.4			
69.7	75.6	2.3			
79.2	72.6	2.2			
82.7	68.2	2.0			
88.2	67.2	2.0			
98.5	62.7	1.9			
103.8	61.9	1.9			
108.8	60.5	1.8			
119.4	56.4	1.7			
124.3	55.3	1.7			
128.7	54.9	1.6			
138.3	52.5	1.5			
143.4	51.8	1.5			
149.2	50.6	1.5			
158.6	47.8	1.5			
60	81.1	4.7	Stacked foils, 13 mg/cm^2 CH,relative, norm. at 50.5 MeV	Hintz	(27)
80	70.5	4.1			
100	61.3	3.6			
93	70.5	3.6	5-mil CH	Aamodt	(26)
144	56.5	1.5			
194	52.0	1.5			
245	49.8	1.2			
263	50.5	2.6			
293	47.7	1.0			
313	47.6	2.1			
240	41.2	0.6			
142	49.4	3.9	Target 1.75 g/cm napthalene crystal,	Cassels	(28)
170 MeV	40.5	2.0	Targets 13 mg/cm CH, 2 % gas loss was corrected by Cumming	Crandall	(29)
204	37.7	1.9			
240	37.9	1.9			
270	36.6	1.8			
295	36.2	1.8			
295	38.7	1.9			
325	36.6	1.8			
320	36.2	1.8			
350	36.7	1.8			
288	33.7	1.2	Targets 0.54 and 0.17 g/cm^2 graphite, calibrated gamma GM counter	Parikh	(30)
313	34.8	1.1			
339	34.9	1.0			
362	32.4	1.0			
388	31.6	1.0			
461	35.3	1.4	Targets 3.7 mg/cm CH ,nuclear emulsion or counter telescope	Rosenfeld	(31)
470	34.1	3.0	no details available	Sorokv	(32)
150	45.0	2.9	Relative measuremcnts normalized at 350 MeV	Ptokodhkin	(33)
260	37.9	2.2			
290	35.9	2.1			
350	35.0				
450	31.1	1.8			
560	29.6	1.7			
660	30.2	1.8			
385	36.7	0.6	Plastic scinti., CH	Andrews	(34)
591	29.9	1.5	Targets 300 mg/cm^2 CH	Goebel	(35)
800	32.0	1.0	0.354 g/cm^2 plas.sci.	Hogostrom	(36)
1 GeV	29.0	1.3	Plastic scint. target	Poskanzer	(37)
1.05	25.0	3.0	Plastic scint. target	Lindstrom	(38)
2.10	26.1	2.4			
2	26.2	0.9	Plastic scint. target scintillator detector	Cumming	(39)
3	26.8	1.0			
3	29.5	1.6	Plastic scint. target	Horwitz	(40)
4.5	26.8	1.7			
6	29.5	1.6			
28	25.9	1.2	Plastic	Cumming	(41)
300	32.0	1.0	Plastic scint. target	Kaufman	(42)

Table 3 Reaction list of $^{63}Cu(p,n)^{63}Cu$

First Author	Place	Ref.	Target (mg/cm^2)*	Incicent (MeV)	Detector	Errors and comment
S.N.Ghoshal	(Berkeley)	(50)	-	3.2-26	GM	typical error:9 %, $T_{1/2}$=38 m, $I_{\beta+}$=93 %, I_{ECK}=7 %.
J.-P.Blaser	(Zurich)	(51)	8.3,0.85	6.45 0.03	GM	not reported, $T_{1/2}$=38 m
J.W.Meadows	(Massachus.)	(7)	0.01"	100, 70 1	GM	relative to $^{27}Al(p,3pn)^{24}Na$
H.A.Howe	(California)	(52)	40	20 0.40 10 0.53 5 0.94	NaIx2	3 % (uncertainty of EC correction is not included), (det.eff.:<1%, stand.source:2 %), $T_{1/2}$=38.3 m $I_{\beta+}$=89.3 %
R.D.Albert	(California)	(53)	1.5	9.85	n long counter	7 % (the detail is not reported)
J.Wing	(Argonne)	(54)	5	10.5 - 4.5 10 0.15 5 0.5	ppc, NaIx2	<10 %, $T_{1/2}$=38.3 m, $I_{\beta+}$=93 %
H.Taketani	(Rochester)	(55)	69.09%: 4.26,5.03 99%:4.43	4.1-6.5 0.1	NaIx2	6 % (T*** thick:3 %, I_{beam}:<3 %, det.eff.:3 %), $I_{\beta+}$=89.8 %
L.F.Hansen	(California)	(56)	1.5-8	5.2 - 11	n long counter	7 % (A long counter was calibrated by $MnSO_4$)
K.Chackett	(Birmingham)	(57)	0.001 in.	9.3 0.3**	NaIx2	4.2 % (stand.source:2 %, beam integrator:1 %)
R.M.Humes	(Ohio)	(58)	not given	6.75	ppc, NaIx2	5.4 % (the detail is not reported)
G.F.Dell	(Ohio)	(59)	2.5 um	6.75	NaIx2	5.4 %, $T_{1/2}$=38 m, $I_{\beta+}$=90 %
J.E.Cline	(Idaho)	(60)	50-1000	590	Ge(Li)	13 % (det.eff.:5 %) relative to $^{27}Al(p,3pn)^{24}Na$

First Author	Place	Ref.	Target (mg/cm^2)*	Incicent (MeV)	Detector	Errors and comment
M.Hille	(Munchen)	(61)	10 um	8.7 - 16 8.7 0.2	Ge(Li)	6 % (det.eff:3 %, statistical:<1 %, photo peak area:3 %, T thick.:3 % I_{beam}:2 %, $T_{1/2}$:1-3 %)
E.Steinberg	(Argonne)	(62)	several	1.5-11.5 GeV	ppc, chem.sep.	5-10 %, monitor $^{27}Al(p,3pn)^{24}Na$
R.Colle	(BNL)	(6)	5-15	2.86-25 0.10	Ge(Li)	7-12 % (I_{beam}:1 %, number of T atoms:1-1.5 %, T thick.:1-1.5 %, statistical:<3 % $T_{1/2}$:3 %, det.eff.:5-10 %, I_γ:1-4 %)
Y. Yoshizawa	(Hiroshima)	(63)	10 um	25-50	GM	10 % (detail is not reported) Isotope Separator on Line was used.
A.Grutter	(Wurenlingen)	(3)	0.1 0.05	16.1-69.8 70 0.53 16 1.6	Ge(Li)	3-5 %, relative to $^{65}Cu(p,n)^{65}Zn$ $T_{1/2}$=38.47 m, I_γ(669.6)=8.40 %
M.E.Sevior	(Melbourne)	(64)	99.89 %	4.21-4.86	BF_3 in paraf.	11 % (I_{beam}:2 %, number of T atoms:2 %, n detection:10 %)

* If unit is not given, the thickness is represented by mg/cm^2.
** Energy spread due to target is included.
*** T: target

Table 4 Reaction list of $^{65}Cu(p,n)^{65}Zn$

First Author	Place	Ref.	Target (mg/cm^2)*	Beam energy (MeV)	Det.	Errors and comment
J.-B.Blaser	(Zurich)	(51)	8.3,0.85	6.5 0.25	GM	not reported, $T_{1/2}$=250 d
J.W.Meadows	(Harvard)	(7)	0.01"	5-100 70 1	GM	relative to $^{27}Al(p,3pn)^{24}Na$
H.A.Howe	(California)	(52)	uniform. <0.5%	10 0.53 5 0.94	NaI	3 % (uncertainty of EC correction is not included), (det.eff.:<1 %, stand.source:2 %), $T_{1/2}$=38.3 m, $I_{\beta+}$=0.893
R.D.Albert	(California)	(53)	1.5	9.85	n long counter	7 % (the detail is not reported)
B.W.Shore	(Massachusetts)	(65)	0.25 mil	7.5	NaI, CsI	3.7 % (weighing:1 %, statistical:1 %, coin:3%, I_{beam}:1 %, beam integrator:<1%, $T_{1/2}$:0.5%)
K.F.Chackett	(Birmingham)	(57)	0.001"	9.3 0.3**	NaI,ppc chem.sep.	3.9 % (calib.source:2 %, I_{beam}:1 %) I_{EC}=98.3 + 0.1 %
J.Wing	(Argonne)	(54)	5	10.5 0.15 5 0.5	NaIx2	<10 % , $T_{1/2}$=245 d, I_γ(1120)=0.49
R.M.Humes	(Ohio)	(58)	-	6.75	NaI,ppc	6.5 % (the detail is not reported)
G.F.Dell	(Ohio)	(59)	2.5 um	6.75	NaI,ppc	5 % (the detail is not reported) $T_{1/2}$=248.5 d, I_γ(1114)=0.49
I.R.Williams	(Oakridge)	(66)	0.005-0.02"	60 0.35 40 0.55	Ge(Li)	30 %, I_{beam}:1 % $T_{1/2}$=245 d, I_γ(1114)=0.45
First Author	Place	Ref.	Target (mg/cm^2)*	Beam energy (MeV)	Det.	Errors and comment
E.Gadioli	(Milano)	(68)	30.91% 42.52mg	10.2-44.3 18 0.25 10 0.35	Ge(Li)	<10%, $T_{1/2}$=246 d, I_γ(1115)=0.49
Z.E.Switowski	(Melborn)	(69)	-	2.15-4.0	BF_3 with paraf.	normalized to 73Co001 data
A.Grutter	(Wurenlingen)	(3)	0.1,0.05	16.1 - 70 70 0.53 16 1.6	Ge(Li)	3-5 %(errors caused by decay data are not included), I_γ(1115)=0.5075
M.E.Sevior	(Melbourne)	(64)	5 keV at 2.2 MeV	2.2-3.2	BF_3 in paraf.	11 % (det.for n:10 %, det.for γ:9 % I_{beam}:2 %, T:5 %, I_γ:2.5 %)
P.Kopecky	(Rez,Czech.)	(70)	22.8	4.42-32.4 32.7 0.2 14.5 0.45 13.0 0.2 4.42 0.4	Ge(Li)	5-8 % (beam integrator:0.5 %, T thick.:1 %, det.eff.:4 %, statistics:<2 %, peak area=1.9-6.8 %)

* If unit is not given, the thickness is represented by mg/cm^2.
** Energy spread due to ttarget is included.
*** T: target

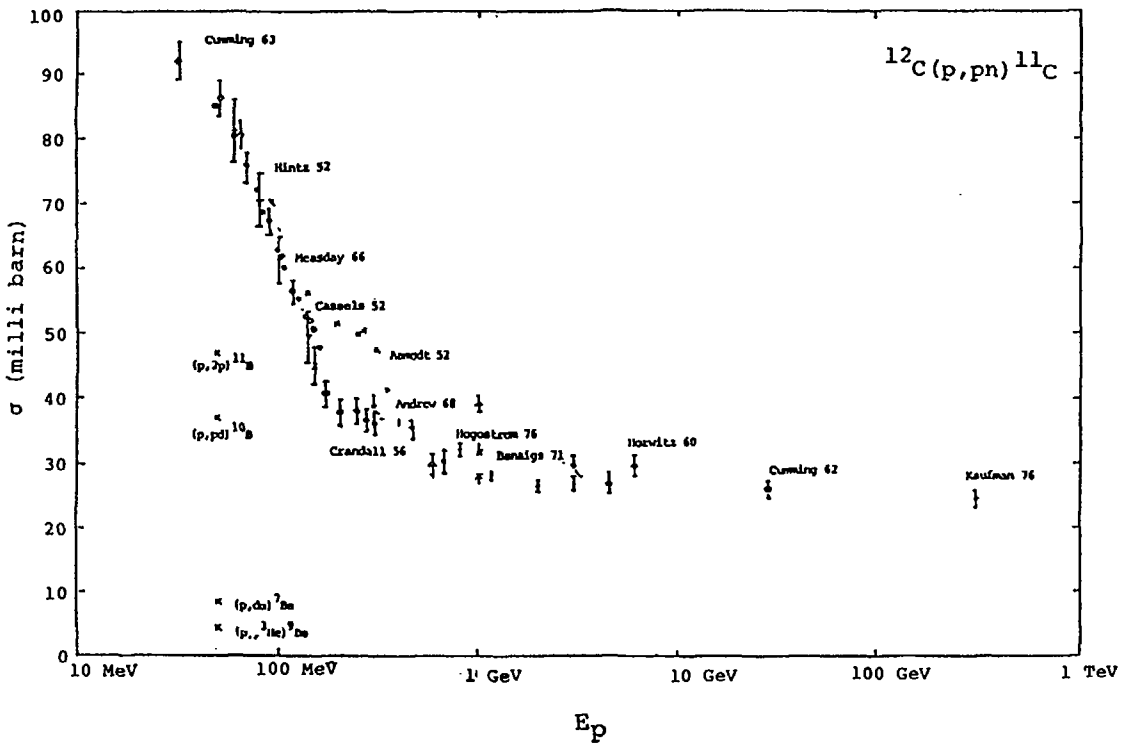

Fig. 1 Cross sections of $^{12}C(p,pn)^{11}C$. All data were not ploted to show cleality of the figure.

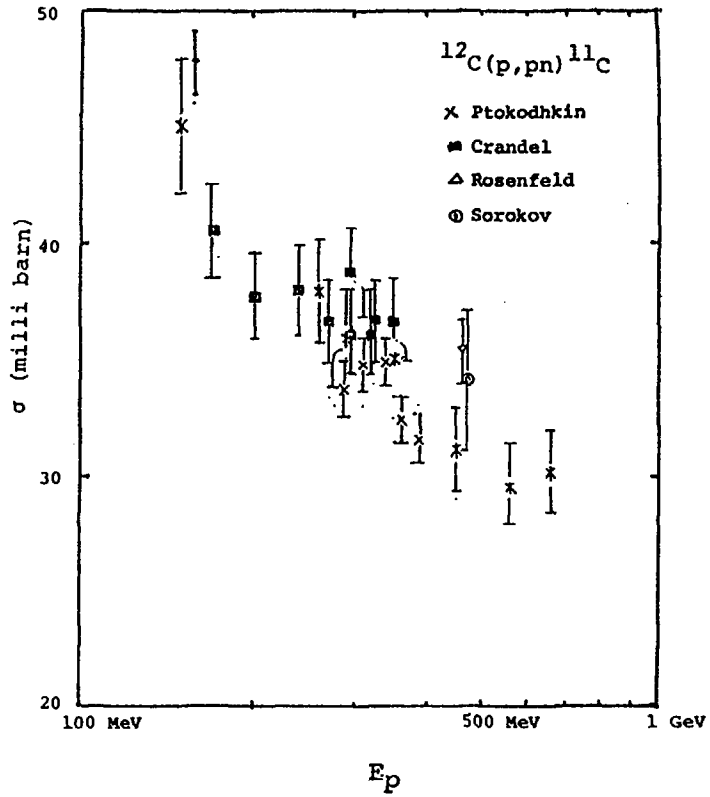

Fig. 2 Cross sections of $^{12}C(p,pn)^{11}C$ in the energy region from 100 MeV to 1 GeV.

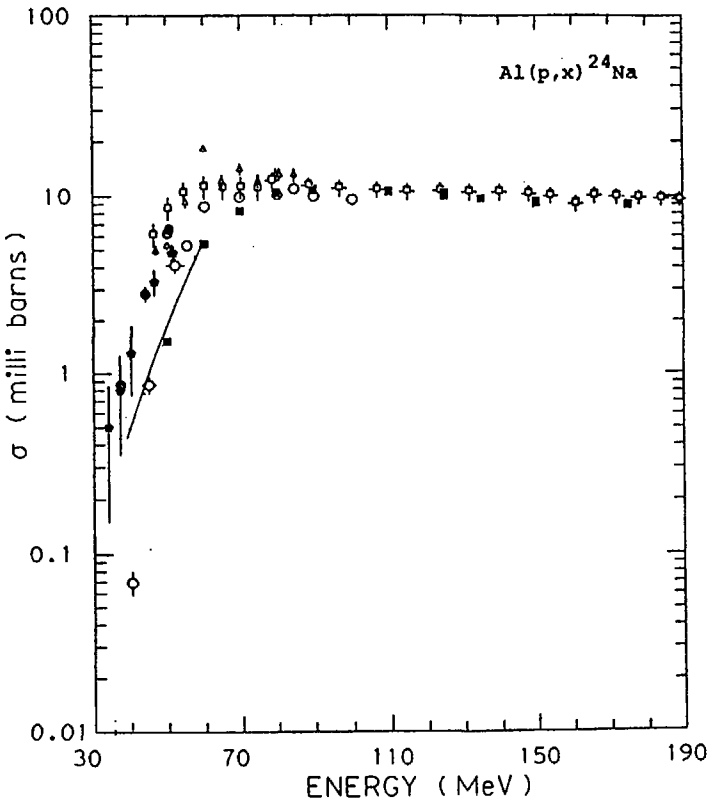

Fig. 3 Cross sections of Al(p,x)^{24}Na. In the figure, the data of ● Cumming[43], ■ Hicks[44], / Williams[45], ◊ Holub[47], ◆ Miano[46], ◇ Hogen[48], and ⊹ Michael[49] were shown.

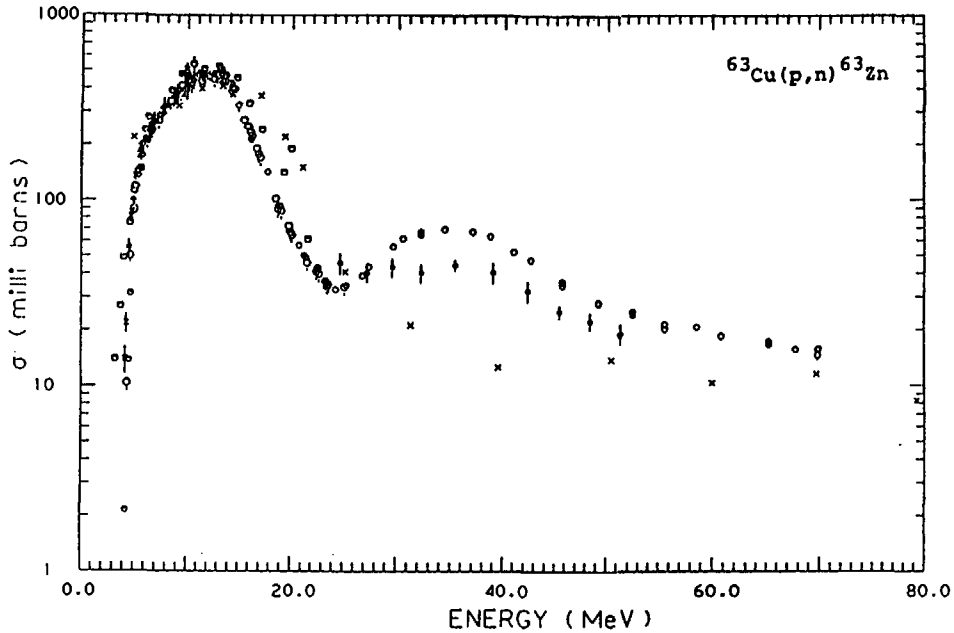

Fig. 4 Cross sections of ^{63}Cu(p,n)^{63}Zn to the 70 MeV of incident energy.

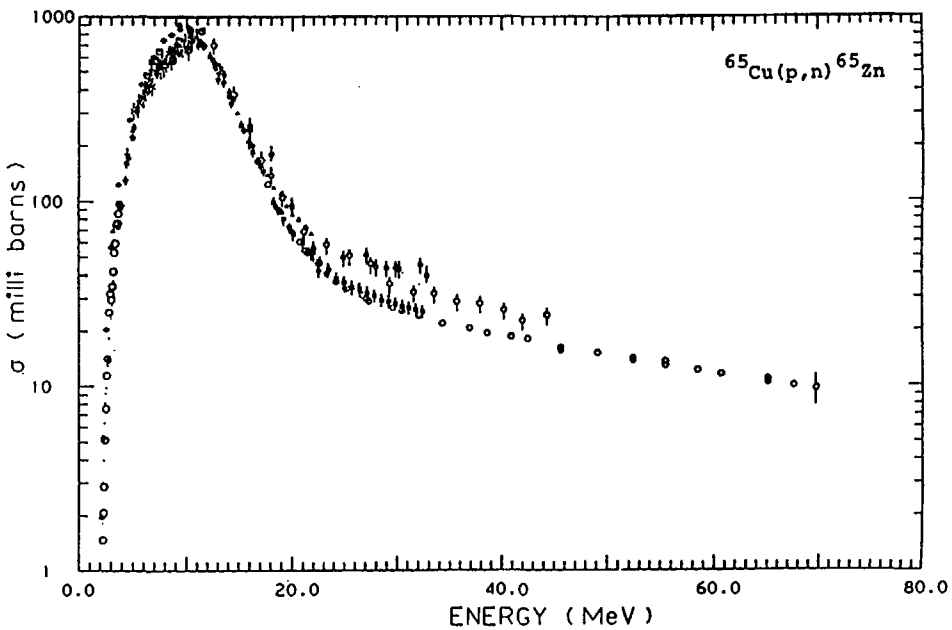

Fig. 5 Cross sections of ^{65}Cu(p,n)^{65}Zn to the 70 MeV of incident energy.

Medical Radioisotope Production in the Middle East and Nuclear Data Needs

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ABSTRACT

The standardization of reported nuclear data for medical radionuclide production could serve: (1) to establish and to maintain international uniformity, (2) to improve the accuracy where this would become necessary, and (3) to help developing laboratories and hospitals. This could include agreement upon: (1) production yields with various types of accelerators under a variety of beam energy and beam current conditions, (2) parameters for optimization of radionuclide purity, and (3) definition of special conditions for routine production. Examples from the current literature are presented. A method for determination of cyclotron beam energy by the Rutherford scattering technique was appended. The experiences of the King Faisal Specialist Hospital and Research Centre in radionuclide and radiopharmaceutical research and the distribution program for medical radionuclides in the Middle East are reviewed.

A CS-30 compact medical cyclotron was commissioned at this institution in 1982. In 1985 a progressive administration organized a department oriented to research, technology transfer and service in radiopharmaceutical science with short-lived cyclotron-produced radionuclides. Reliable operations have been achieved by: (1) Recruitment of research-oriented, flexible individuals with an international cross section of chemical and cyclotron expertise that do respond to unexpected problems characteristic of developing facilities; (2) availability of hot cell facilities and analytical instrumentation; (3) a reliable voltage-stable local power grid; (4) a departmental shop equipped to design and fabricate targetry and components, and to maintain equipment; (5) procurement of an ample stock of supplies and spare parts as deliveries average 9±2 months; and (6) a sincere effort to train Saudi nationals in all aspects of the program.

The radionuclide production and distribution program is presently comprised of six (6) radioisotopes (^{67}Ga, ^{81}Rb-^{81m}Kr, ^{111}In, ^{123}I, and ^{201}Tl) in eight (8) radiopharmaceuticals and two (2) additional radiochemical forms. Two (2) additional radiopharmaceuticals (^{111}In and ^{124}I) are being qualified for human use. Several other short-lived radionuclides (^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{38}K, ^{44}Ti-^{44}Sc, ^{45}Ti, ^{82}Sr-^{82}Rb, ^{92}Tc, ^{99m}Tc, ^{123}Cs-^{123}Xe-^{123}I, ^{124}I and ^{211}At) are being considered for various research activities.

The radiopharmaceuticals are manufactured by adhering to the good manufacturing practices recommended by the U.S. Food and Drug Administration and insistence upon the highest quality control standards. The radionuclides are packaged and transported within the Kingdom and to adjoining Arab States in a timely manner via Saudia or car according to the internationally accepted regulations recommended by the IAEA.

From the viewpoint of being the only Research Centre in the Middle East with a medical radionuclide research and production program we are able to identify nuclear data needs that would assist our ambitious program.

Specifically, we are interested in the following nuclear reactions:

$^{38}Ar(p,n)^{38}K$, $^{40}Ar(p,3n)^{38}K$, $^{92}Mo(p,n)^{92}Tc$, $^{100}Mo(p,2n)^{99m}Tc$, $^{112}Cd(p,2n)^{111}In$, $^{82}Kr(p,2n)^{81m+g}Rb$; $^{82,83,84}Kr(d,xn)^{81}Rb$, $^{82,83,84}Kr(^{3}He,xn)^{82}Sr$, $^{82,83,84}Kr(^{4}He,xn)^{82}Sr$, $^{124}Xe(p,2n)^{123}Cs$-^{123}Xe-^{23}I, $^{124}Xe(p,pn)^{123}Xe$-^{123}I, $^{124}Xe(p,2pn)^{123}I$, $^{124}Xe(p,3n)^{122}Cs$-^{122}Xe-^{122}I, $^{124}Xe(p,2pn)^{122}Xe$-^{122}I, $^{126}Xe(p,pn)^{125}Xe$. In addition, we have concerns about the nuclear decay schemes of ^{77m}Br, $^{107m+g}In$, $^{108m+g}In$ and ^{123}Xe.

The IAEA consultants' meeting on "Data Requirements for Medical Radioisotope Production" provide an overdue opportunity to advocate standardization of reported data required by users. Criteria for the publication of medical radioisotope production data in the scientific literature can now be openly discussed and recommendations advanced. These criteria include amplification of the following topics of interest to the radiochemist involved in a medical program utilizing accelerator technology. That is:

- type of accelerator and energy resolution
- beam current measurements
- energy calculation of medical cyclotrons
- absolute cross section measurements
- monitor reactions
- radiation detectors and criteria of calibration
- traceability of reference standards
- uncertainty of measurements
- target matrix composition and uniformity
- recoil losses, gas density or plasma effects
- uniformity and agreement of reported units for the production yield
- optimization of radionuclidic production yields
- minimization of radionuclidic impurities
- requirements for enriched isotopic targets.

The standardization of reported nuclear data for medical radionuclide production could serve: (1) to establish and to maintain international uniformity; (2) to improve the accuracy, where this would become necessary; and (3) to help developing laboratories and hospitals. This could include agreement upon: (1) production yields with various types of accelerators under a

variety of beam energy and beam current conditions; (2) parameters for optimization of radionuclidic purity; and (3) definition of special conditions for routine production.

Several examples from the current literature will be shown to demonstrate the lack of consistency in the manner in which data are reported, particularly for production yields. This author prefers the use of the definition of the thick target production yield, Y, as a saturation activity. This results in Y being described independent of the irradiation time and the half-life of the product radionuclides. In addition, it is easily evaluated from the excitation function. In many instances, the thick target production yield is as useful as the excitation function to the radiochemist involved in medical radioisotope production, because it represents what is actually obtained under a set of optimized routine production conditions. Obviously, without knowledge of the excitation function, the radiochemist is left not knowing what fraction of the theoretical yield he is actually obtaining. Therefore, the information assists to optimize target design.

Several examples of recently published excitation functions now ready for evaluation are referenced. These include cross section measurements and thick target yields on ^{14}N, ^{15}N and ^{16}O targets as reported by Sajjad, et.al. (1) for the production of ^{13}N and ^{15}O with protons and deuterons. The $^{209}Bi(\alpha,2n)^{211}At$ excitation function and nuclear data for ^{211}At was recently re-investigated by Mirzadeh, et.al. (2). Production of the ^{211}Rn-^{211}At generator via ^{7}Li induced reactions on ^{209}Bi may be one of the first examples (3) of heavy ion induced reactions for medical radioisotope production.

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HIGH-ENERGY PROTON INDUCED REACTIONS FOR THE PRODUCTION OF FLUORINE-18

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A B S T R A C T

Fluorine-18 is a positron-emitting radionuclide of great interest in the applications of computer assisted positron-emission tomography. The production of ^{18}F via proton induced reactions on a series of low-Z targets was studied. External beams of protons of 67.5 MeV were used to bombard Na, Mg, and Al targets and the resulting ^{18}F-induced radioactivities were measured using gamma-ray spectrometry. Cross sections (mbarn) and yields (mCi/μAh) were then calculated in the 67.5- to 20-MeV energy range. Thick-target ^{18}F yields were measured as 88 +/- 12 mCi/μAh for Na (67-21 MeV) targets; 26 +/- 3.5 mCi/μAh for Mg (67-25 MeV) targets; and 23 +/- 3 mCi/μAh for Al (67-22 MeV) targets. These methods are also compared on the basis of experimental results and using theoretically-predicted cross sections from a modified ALICE 82 (named ALISO) code. Finally, the potential of these methods for the large-scale production of ^{18}F is also discussed.

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I. INTRODUCTION

Among the many short-lived positron emitters that are currently in use or under development for applications in diagnostic nuclear medicine, the uses of 109.77-min ^{18}F; 20.38-min ^{11}C; 9.97 min ^{13}N; and 2.04 min ^{15}O are clearly in the forefront[1]. This is easily shown by the fact that state-of-the-art techniques for their accelerator production (including specialized low-energy accelerators) are currently available, as well as by the number and the variety of "PET" radiopharmaceuticals already in use in many clinical programs in the USA and abroad[2,3].

Currently, low-energy (> 10- to 22-MeV) accelerators are the major source of ^{18}F using the $^{18}O(p,n)^{18}F$ (Q= - 2.4 MeV) reaction. In addition, the $^{20}Ne(d,\alpha)^{18}F$ (Q= 2.8 MeV) reaction is also utilized in accelerators having deuteron beam capabilities[4]. This latter method provides several hundreds millicurie batches of ^{18}F, while Ci-level batches have been obtained with proton beams on enriched ^{18}O-H_2O targets[5,6]. On a minor scale, 40-MeV proton beams are also being used on Ne gas targets to produce ^{18}F with a similar Ne/F_2 target and processing system as used in (d,α) method[6]. However, no work has been previously reported on the use of higher energy proton-induced reactions to produce ^{18}F from other low-Z targets. In low-Z targets such as Na (Z=11); Mg (Z=12); and Al (Z=13); alpha particles are weakly bound to the nucleus and, therefore, reactions inducing the emission of alpha particles are expected to have significant cross sections despite their higher Coulomb barriers. As the energy of the proton beam is increased, compound-nucleus reactions in which several particles are emitted begin to predominate with respect to other reaction channels involving stripping or pick-up mechanisms [7]. Because of the above physical viewpoint, a systematic study on the potential of high-energy proton reactions on Na, Mg, and Al was initiated at UC Davis. When preliminary results indicating a significant fraction of ~ 2-h long 511-keV photons was observed in thick Na, Mg, and Al targets, a detailed study to measure cross sections and yields was initiated. The results of these experiments are given here. The potential of these methods on the future availability of ^{18}F is also discussed. A comparison to the current ^{18}F-production methods is also made. Finally, these experimental results are compared with the ALICE 82 code for calculating total cross sections[8].

II. EXPERIMENTAL

The Crocker Nuclear Laboratory's 1.93-m (76-in) isochronous cyclotron at the University of California, Davis, was used for all the irradiations. An external proton beam of 67.5 +/- 0.1 MeV of intensities up to 15 μA was used in the irradiation of solid target materials. For the cross section and yield measurements, the targets were irradiated with 100 +/- 10 nA beams in an specially constructed low-intensity beam target as previously reported for this type of experimentation [9].

Both thin- and thick targets were constructed with NaCl, Na_2CO_3, or Na(s) (Mallinckrodt Chemicals Inc., St Louis, Mo.) for the Na reactions; MgO, $Mg(OH)_2$, (Mallinckrodt Chemicals Inc., St. Louis, Mo.) for the Mg reactions; and Al(s) (Alfa Inorganics, Danvers, Massachusetts) for the Al reactions. Metallic Mg was not used as target material due to the difficulties in preparaing thin targets. All of these targets were found to be acceptable for the low-current irradiations (< 100 nA). However, when thick-target experiments at higher currents (> 5 μA) were conducted, Na(s), NaCl, and Al targets seemed the best alternatives with high stability for radiation- and/or temperature-induced decomposition.

The stack-target technique was used for the cross section and thin-target yield measurements in the 67.5- to 20-MeV energy range covered in this work. However, due to logistic limitations in radioassaying numerous single targets, the full energy range covered here was measured in three or more sections.

Thin targets (~ 0.05 cm) were prepared from the different target materials. The salt targets were used after drying in an oven (120°C) for several hours prior to forming and pressing (~ 0.15 Pa) into cylindrical shapes supported by an Al washer (0.050-cm thick, 1.27-cm i.d, 2.54-cm o.d.). These targets were subsequently stored inside a dessicator prior to use. The area of the target exposed to the proton beam was limited to less than 0.079 cm^2 by 0.318-cm i.d. (0.125-in) double collimators up front and close (2.5 cm) to the stack of targets. In this manner, the induced radioactivities were approximated to a point-source geometry required for accurate radioassay. Thick targets were also prepared to measure yields in different proton-energy ranges, and for comparison with calculated cumulative thin-target yields. The thick targets were also prepared by machining the solid metals or by pressing the salts into Al-made holders. These thick targets were irradiated in the same target holder (water cooling was added) as previously described, but with beam intensities up to 5 μA. All the radioassays were conducted with a NBS calibrated high-purity Ge detector coupled to a 8192-multichannel analyzer. All the measurements were performed at either 10-, 20-, or 30-cm distance from the detector. The analyses of induced radioactivities were conducted using the characteristic 511-keV photons. However, because other shorter-lived positron emitters (i.e. 2.5-m ^{15}O; 10-m ^{13}N; and 20-m ^{11}C) are also formed, each different target material was used to determine a time interval (decay time) after the end-of-bombardment (EOB) at which ^{18}F radioactivities could be measured accurately with a minimum or no interference from other positron emitters. Half-life measurements were also conducted to confirm the identity and purity of the induced ^{18}F radioactivities. The results of these latter measurements for all the different targets were conclusive to determine the radionuclidic purity of the ^{18}F produced.

The analysis of the data and the evaluation of uncertainties for the measurements and results reported here, were performed based upon methods previously reported[10]. The total uncertainties for thin- and thick-target yields and the total cross sections are given to one standard deviation and amounted to +/- 13.5% (1 sigma). On the other hand, the uncertainties in the incident and exit energies calculated for the stack of targets, ranged from +/- 0.3% (0.2 MeV) for the external 67.5-MeV proton beam, to +/- 1.3% (0.5 MeV) at 40 MeV, and +/- 3% (0.6 MeV) at 20 MeV. The total uncertainties in the energy calculations are also given with a one-standard deviation confidence level.

Other gamma-ray emitting radionuclides were also identified as resulting from the direct interaction of the proton beam with the target material. Sodium-22 (2.6-y) was positively identified. In addition, 15-h ^{24}Na was also identified in all the different targets. In the Na-containing targets, ^{24}Na may have been produced as a result of secondary neutron interactions in the target (i.e. $^{23}Na[n,\gamma]$). Beryllium-7 (53.28 d) was also detected as a trace-level impurity in targets containing oxygen and/or carbon, but was undetected in Al targets.

III. RESULTS AND DISCUSSION

^{18}F Yields and Total Cross Sections.

The calculated Q values and energetic thresholds for the different reaction channels studied in this work are given in tables 1-3, for Na, Mg, and Al targets, respectively. The experimental yields (single and cumulative) for the production of ^{18}F using high-energy proton beams are shown in fig. 1-3, for Na, Mg, and Al targets, respectively. In addition, the single and cumulative yields for ^{24}Na and ^{22}Na are also shown in these figures. A comparison of the ^{18}F single and cumulative ^{18}F yields and the total cross sections for the production of ^{18}F from on Na, Mg, and Al targets, are shown in figs. 4 and 5, respectively. Because several stack-target experiments were conducted for each of the different target materials, the results given here are averages of several individual measurements. The radionuclide yields (mCi/μAh) and the total cross sections

(mbarn) were calculated according to already reported methods[11]. Because an excellent agreement was observed when combining and averaging the individual experiments, the final results reported here are indicated with an eye-fitted line to the experimental data. This method was found necessary because of the minor but significant differences in energy ranges (i.e. target thicknesses) obtained when preparing all of the necessary sets of single thin targets.

Because different reaction channels are energetically feasible when high-energy protons are used, the total cross section represents the overall effect of all these channels in a natural isotopic target (^{23}Na 100%; ^{24}Mg 78.99%, ^{25}Mg 10.00%, ^{26}Mg 11.01%; ^{27}Al 100%). While there may be an interest in resolving these channels from the physical standpoint, in terms of radionuclide production, the total cross section is sufficient for the purpose of evaluating these reactions. Furthermore, because these different channels do not affect the radionuclidic purity of the desired ^{18}F product, resolving the contributing reaction channels is not necessary.

For Na targets, the cumulative ^{18}F yield in the 67.5- to 25.1-MeV energy region was measured as 88 +/- 12 (13.5%) mCi/μAh (see fig. 1). In addition, the maximum of the total cross section for the production of ^{18}F was found at 42-44 MeV, and measured as 45 +/- 6 (13.5%) mbarn (see fig. 5). For Mg targets, the cumulative ^{18}F yield was lower and measured as 26 +/- 3.5 (13.5%) mCi/μAh in the 67- to 25-MeV energy range (see fig. 2). In addition, the total cross section was significantly lower, and equal to 22 +/- 3 (13.5%) mbarn, with a maximum at a higher energy (62-64 MeV; see fig. 5). For Al targets, the cumulative ^{18}F yield was found to be 23 +/- 3 (13.5%) mCi/μAh in the 67- to 22-MeV energy range (see fig. 3), and the maximum in the total cross section was measured as 8 +/- 1 (13.5%) mbarn at 60-62 MeV (see fig. 5).

^{24}Na and ^{22}Na Yields

Sodium-24 (15.03 h) and ^{22}Na (2.602 a) were the only radionuclide impurities detected and reported in these experiments. Beryllium-7 (53.28 d) was also detected in C and O containing target materials. However, if any of these methods is applied for the large-scale production of ^{18}F, the use of metallic Na, Mg, and/or Al targets would eliminate ^{7}Be production. Furthermore, these impurities (including ^{7}Be) are expected to be eliminated during the radiochemical processing of the target materials. In any case, as shown in fig. 1-3, the yields of these impurities are much lower than the ^{18}F yields measured in this work. In the energy regions covered in this work, the cumulative yields were measured as:

(a) Na targets; 14 +/- 2 μCi/μAh and 76 +/- 14 μCi/μAh for ^{22}Na and ^{24}Na, respectively, in the 67- to 25-MeV energy range;

(b) Mg targets; 9 +/- 1 μCi/μAh and 1.8 +/- 0.2 mCi/μAh for ^{22}Na and ^{24}Na, respectively, in the 67- to 25-MeV energy region; and

(c) Al targets; 13 +/- 2 μCi/μAh and 3.5 +/- 0.4 mCi/μAh for ^{22}Na and ^{24}Na, respectively, in the 67- to 7-MeV energy region.

Both, Mg and Al targets produced considerably higher ^{24}Na than the Na targets. This is most likely due to the presence of other proton-induced reaction channels not present in Na targets where the production of ^{24}Na is expected to be due to secondary neutrons.

Comparison of ^{18}F Production Methods

With the above given information, a comparison of the different methods for the production of ^{18}F is appropriate. Table 4 gives a summary of the different reactions used today for the production of ^{18}F. Clearly, the use of protons on Na targets appear to offer the greatest potential for large-

scale production of ^{18}F. Experimentation being conducted at UC Davis using a thick (3 cm) 67- to 40-MeV metallic Na target with a 5-7 μA proton beam has consistently yielded an average of 125 +/- 10 mCi/μAh (n= 8) of ^{18}F. A radiochemical method for the separation of ^{18}F from the Na target is being developed. Currently > 90% efficiency in isolating ^{18}F as fluoride has been achieved and will be reported elsewhere[19]. A Na metal target system could then offer significant advantages over other methods currently in use, if a > 65-MeV proton accelerator is available. Because Na is an exellent cyclotron target material, high intensity beams are possible in relatively small targets (< 1 g). Furthermore, for the production of Ci-levels of aqueous ^{18}F-fluoride, the use of remote/automatic handling of target and radiochemistry appears quite feasible.

As of this date, Mg targets have not been investigated as a source of large amounts of ^{18}F. It appears that due to the similarity in cross sections and yields (see fig. 4) when compared to Al targets, there are no immediate advantages on its use. However, the use of Na or Al targets appears to offer other desirable alternatives and potentially many significant advantages as is explained and discussed below.

Use of ^{23}Na and ^{27}Al targets.

Many reaction channels leading to the formation of ^{18}F are energetically possible with 67.5 MeV protons on Na and Al targets (see tables 1 and 3). Among these channels, the reactions:

$$^{23}Na(p,\alpha 2n)^{18}Ne\ (1.67\ s) \rightarrow ^{18}F\ (Q= -26.1\ MeV) \quad (1)$$

$$^{27}Al(p,2\alpha 2n)^{18}Ne\ (1.67\ s) \rightarrow ^{18}F\ (Q= -36.22\ MeV) \quad (2)$$

appears to be significant contributing channels for the indirect production of ^{18}F. Computer-based code calculations using ALISO [8], indicated that approximately 25% of the total production of ^{18}F occurs via the production of the 1.67-s ^{18}Ne parent. This relative contribution has not been determined experimentally. However, a significant amount of "easily removable" ^{18}F has been detected in several thick targets used in yield measurements and radiochemistry. Direct determinations with on-line gamma-ray spectrometry (using the 1.04-MeV gamma-ray from ^{18}Ne) are planned.

The production and fast removal of the 1.67-s ^{18}Ne radioactivities from a beam-heated or molten Na or Al target, would allow the operation of generator-type system for the production of ^{18}F. A generator system of this type would offer many advantages. These aspects are discussed below.

Potential uses and advantages of the $^{18}Ne \rightarrow ^{18}F$ generator

The potential use of the 1.67-s ^{18}Ne parent as a gaseous generator of ^{18}F have already been reported[24]. In principle, the $^{18}Ne \rightarrow ^{18}F$ generator should allow the development of an on-line, continuous flow, phase (gas/solid or gas/liquid) separation of the parent ^{18}Ne (gas) from the target and the radionuclidic impurities. This generator system would be similar to the continuous-flow production of ^{123}Xe (gas) from a molten NaI-target already developed at UC Davis for the large-scale production of ^{123}I[25,26]. However, many design and operational differences are worth discussing since no practical applications of this generator have been reported. The $^{18}Ne \rightarrow ^{18}F$ generator has the following advantages for the large-scale production of ^{18}F using Na or Al targets:

(1) It uses a simple, inexpensive, chemically and radiolytically stable target.
(2) The relatively low melting points (Na 97.8°C; Al 660°C) and high boiling points (Na 892°C; Al 2467°C) of these targets should provide a wide temperature range in which to operate using high beam intensities.
(3) The gas/liquid (molten) phase separation of the ^{18}Ne produced in the target can be continuosly swept away from the irradiation zone with a stream of He gas. In this manner, the purification of ^{18}Ne from the target material

and from the radionuclide impurities, can be performed by physical, rather than chemical means. This physical method should be simpler, more efficient, and safer for personnel. In addition, diffussion of Ne from a hot (i.e. beam-heated) target may be fast to allow purging of ^{18}Ne from the target chamber into a closely located trap.

(4) Once away from the irradiation zone, the short-lived 1.67-s ^{18}Ne will promptly decay to ^{18}F. This ^{18}F can then be washed from the walls of the container with different aqueous or organic solvents.

A ^{18}Ne -> ^{18}F generator system could then provide an essentially unlimited number of sequential batches of ^{18}F in different solvents. However, the key factor for a generator of this kind is to obtain an efficient and rapid release of Ne from the target. Experiments to determine this factor are in progress.

Potential availability of ^{18}F from Na, Mg, and/or Al targets

It appears that with the possible exception of Na targets (see fig. 4) the major disadvantage of these methods is the lack of an adequate number of > 65 MeV proton accelerators. As of this date, few proton accelerators dedicated to medical radionuclide production can operate at energies > 45 MeV. In addition to the UC Davis's 76-in. cyclotron, several other R&D facilities such as the Brookhaven National Laboratory in New York, the Swiss Institute of Nuclear Sciences in Wurlingen, Switzerland, the TRIUMF facility in Vancouver, British Columbia, and the National Accelerator Center, in Capetown, South Africa, have the beam energy (i.e. > 65 MeV) and intensity (tens of uA) capabilities in addition to active R&D programs in PET radiopharmaceuticals required to take advantage of these methods. In the private sector, 70-MeV accelerators in USA and Japan have recently been installed and began operating with several tens of microamperes of external proton beams. These accelerators also have several hundreds of microamperes of internal proton beam capabilities. It is, therefore, conceivable that in the future these facilities could produce several Ci batches of ^{18}F on a daily basis, and thus support R&D and some of the local clinical needs for several ^{18}F-labeled radiopharmaceuticals. It also appears that in order to maximize the use of these low-Z targets, the current state-of-the-art in high intensity targets is at least adequate to explore the use of molten or solid metallic targets capable of withstanding the deposition of several kW of beam power. There is also the potential of using higher internal beams which is as of to-date an untested potential, but also worth of consideration.

Theoretical and experimental cross sections

A comparison of the experimental cross sections for the production of ^{18}F reported here and theoretically calculated values obtained from the ALISO code[8] is given in table 5. There is a good general agreement in the shape of the experimental excitation functions as shown in fig. 5 with the calculated values provided by the code. This suggests that the use of the ALISO code could provide an excellent prediction on the usefulness of this type of reactions. However, in order to test this code with other type of reactions and targets, a full evaluation with other experimental cross sections is also needed. This evaluation is in progress at the University of California at Davis.

IV. CONCLUSIONS

The production of ^{18}F using high-energy protons on Na, Mg, and/or Al targets appears to be a method that offers some advantages over existing techniques. Higher yields are possible, with the added potential that several radiochemical forms of electrophillic and nucleophillic ^{18}F may be possible from a single target system. It is also conceivable that a tanden

target (i.e. Al and Na) may yield several Ci-level batches of ^{18}F in various solvents, from a single irradiation. However, the major drawbacks for these methods includes the need of high-energy proton beams (> 65 MeV) for maximizing production yields, and the need to develop a continuous-flow (i.e. generator type), molten or beam-heated target system to take full advantage of the indirect production of ^{18}F via the $^{18}Ne \rightarrow {}^{18}F$ parent-daughter system. The use of Na targets offers the possibility of the highest ^{18}F yield in comparison to previously reported methods.

Any of the targets reported in this work have the potential to provide sufficient ^{18}F in different radiochemical forms for use in the development of PET radiopharmaceuticals and for increasing the variety of PET diagnostic procedures. This latter aspect seems also necessary for improving the economic basis for operating PET systems for routine diagnosis of several diseases. While most current PET R&D activities are centered at in-house medical/research institutions with accelerator; radiochemistry/radiopharmaceutical; PET imaging cameras; and data-handling capabilities, the full potential of PET techniques will only be realized when a range of diagnostic procedures are routinely available for the diagnosis of brain, heart, tumors, and many other anatomic/physiologic disorders. The development of production methods for making available positron-emitting radionuclides is therefore, of great interest and usually it is a determining step in the evaluation and/or clinical implementation of new procedures. The supply of PET radionuclides (or of many generator systems being developed) would then depend on the service radiopharmaceutical industry operating accelerators for medical radionuclide production. The development of new proton accelerators, in particular negative-ion (H^-) accelerators, with sufficient capabilities for producing large amounts of radionuclides should be continued. When available, the use of these accelerators, however, would also depend on a succesful and parallel development of new target systems capable to operate routinely under the effects of high beam-power deposition. Because these negative-ion accelerators also have the potential capability to operate with simultaneous dual beams of equal or different energies, the development of multiple target systems to share a fraction of the accelerator's high current beams, is clearly a concurrent need.

The ^{18}F total cross sections measured in this work are quite similar to those calculated with a compound-nucleus type computer-based code (ALICE 82/ALISO). Small quantitative discrepancies suggest that some modifications to the input parameters to these codes may be necessary when used in calculating cross sections for proton induced reactions in low-Z target materials.

Finally, the advantages offered by any of these methods will only materialize if proton accelerators of sufficient energy and beam intensities, and the necessary targetry and radiochemistry methodology required for preparing ^{18}F for radiopharmaceutical use, continues to be developed. The application of these concepts is presently being studied at the University of California, Davis.

A C K N O W L E D G E M E N T S

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TABLE 1. Nuclear reactions on ^{23}Na targets leading to the direct or indirect production of ^{18}F with proton beams(*).

Nuclear Reaction	Q value (MeV)	Energetic Threshold (MeV)
^{23}Na (p,α 2n) -> ^{18}Ne (1.67 s) -> ^{18}F	- 26.1	27.3
^{23}Na (p,α pn) ^{18}F	- 20.9	21.8
^{23}Na (p,α d) ^{18}F	- 18.7	19.5

(*) Atomic masses for these calculations were obtained from Nuclear Data Tables 9, 4-5 (1971).

TABLE 2. Nuclear reactions on Mg targets leading to the direct or indirect production of ^{18}F with proton beams(*).

Nuclear Reaction	Q value (MeV)	Energetic Threshold (MeV)
^{24}Mg (78.99%) Reactions		
^{24}Mg (p,α3n) ^{18}Na ---> ^{18}F	- 58.8	61.2
^{24}Mg (p,α p2n) ^{18}Ne ---> ^{18}F	- 37.8	39.3
^{24}Mg (p,α 2pn) ^{18}F	- 32.6	33.9
^{24}Mg (p,7n) ^{18}Al ---> ^{18}F	- 60.9	63.4
^{25}Mg (10.00%) Reactions		
^{25}Mg (p,α 4n) ^{18}Na ---> ^{18}F	- 66.1	68.7
^{25}Mg (p,α3pn) ^{18}Ne ---> ^{18}F	- 45.2	47.0
^{25}Mg (p,α 2p2n) ^{18}F	- 39.9	41.5
^{25}Mg (p,2α) ^{18}F	- 11.6	12.1
^{25}Mg (p,8n) ^{18}Al ---> ^{18}F	- 68.3	71.1
^{26}Mg (11.01%) Reactions		
^{26}Mg (p,α 5n) ^{18}Na ---> ^{18}F	- 68.5	71.2
^{26}Mg (p,α p4n) ^{18}Ne ---> ^{18}F	- 47.6	49.4
^{26}Mg (p,α2p3n) ^{18}F	- 42.3	43.9
^{26}Mg (p,2α n) ^{18}F	- 14.0	14.5
^{26}Mg (p,9n) ^{18}Al ---> ^{18}F	- 70.7	73.4

(*) Atomic masses for these calculations were obtained from Nuclear Data Tables 9, 4-5 (1971).

TABLE 3. Nuclear reaction on ^{27}Al targets leading to the direct or indirect production of ^{18}F with proton beams(*).

Nuclear Reaction	Q value (MeV)	Energetic Threshold (MeV)
^{27}Al (p,2α d) ^{18}F	- 28.76	29.80
^{27}Al (p,2α pn) ^{18}F	- 30.99	32.11
^{27}Al (p,2α 2n) ^{18}Ne (1.67 s) -> ^{18}F	- 36.22	37.52
^{27}Al (p,αtdp) ^{18}F	- 48.58	50.33
^{27}Al (p,α3d) ^{18}F	- 52.61	54.50
^{27}Al (p,α3p3n) ^{18}F	- 59.28	61.42

(*) Atomic masses for the calculations of Q values and energetic threshold were obtained from Nuclear Data Tables 9, 4-5 (1971).

TABLE 4. Nuclear reactions for the production of ^{18}F.

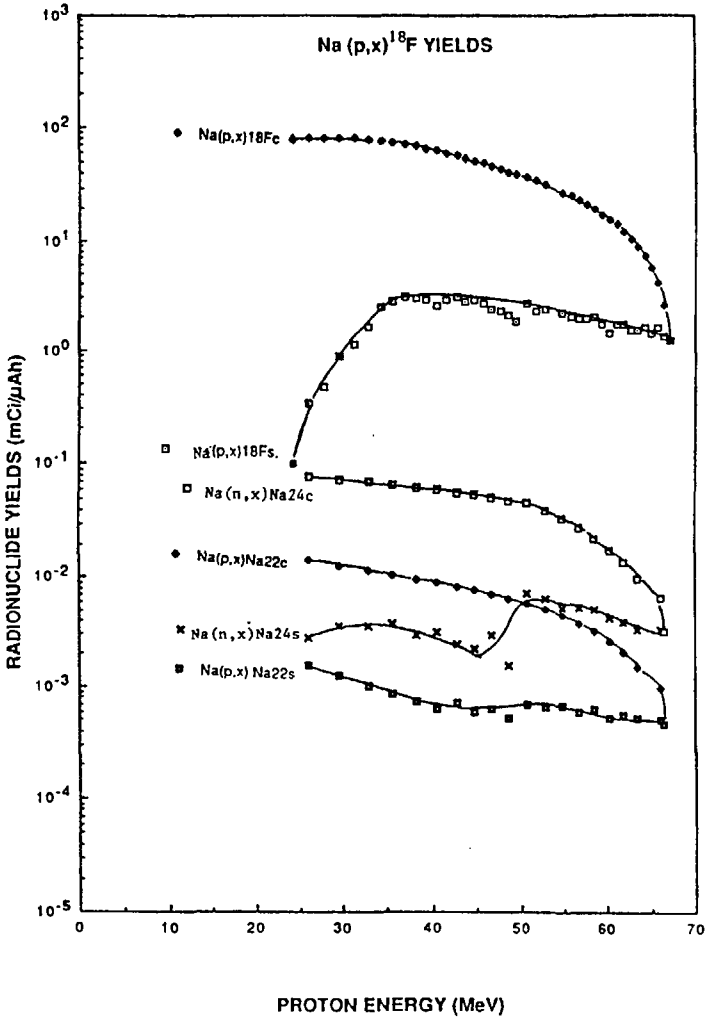
Nuclear reaction	Energy range (MeV)	Thick target yield (mCi/μAh)	References
(A) PROTON REACTIONS			
$^{18}O(p,n)^{18}F$	20 to 3	90	Shaeffer et al.[12] Wieland, Highfill[13]
$^{20}Ne(p,2pn)^{18}F$	41 to 35	15	Ruth[14]
	450	1.5	Ruth et al.[15]
$^{27}Al(p,2\alpha\,2n)^{18}Ne\rightarrow^{18}F$	67 to 50	20	Lagunas-Solar et al.[16]
$(p,2\alpha\,pn)^{18}F$			
$(p,2\alpha\,d)^{18}F$	67 to 7	23.2	Lagunas-Solar et al.[16]
$^{23}Na(p,\alpha\,2n)^{18}Ne\rightarrow^{18}F$	67 to 22	88	Lagunas-Solar et al.[17]
$(p,\alpha\,pn)^{18}F$	67 to 22	88	
$(p,\alpha\,d)^{18}F$	67 to 22	88	
$^{23}Na(m)\ (p,x)\ ^{18}F$	67 to 40	125 (**)	Lagunas-Solar et al.[19]
$Mg(nat)(p,x)^{18}Ne\rightarrow^{18}F$	67 to 25	26	Lagunas-Solar et al.[18]
(B) DEUTERON REACTIONS			
$^{20}Ne(d,\alpha)^{18}F$	18 to 2	34	Nozaki et al.[4]
$^{20}Ne(d,x)^{18}Ne\rightarrow^{18}F$	65 to 60	5	Backhausen et al.[20]
(C) ALPHA REACTIONS			
$^{16}O(\alpha,d)^{18}F$	40 to 22	11	Nozaki et al.[4]
$^{16}O(\alpha,2n)^{18}Ne\rightarrow^{18}F$	52 to 4	7(*)	Lindner et al.[21]
(D) HELIUM-3 REACTIONS			
$^{16}O(^3He,n)^{18}Ne\rightarrow^{18}F$	41 to 14	13	Fitschen et al.[22]
$^{20}Ne(^3He,\alpha\,p)^{18}F$	35 to 5	17	Nozaki et al.[4]
$^{20}Ne(^3He,\alpha\,p)^{18}F$	56 to 10	25	Lambrecht et al.[23]
$(^3He,\alpha\,n)^{18}Ne\rightarrow^{18}F$			

(*) Experimental yield (**) Thick-target experimental data.

TABLE 5. Comparison of theoretical and experimental cross sections for the production of ^{18}F from Na and Al targets (*).

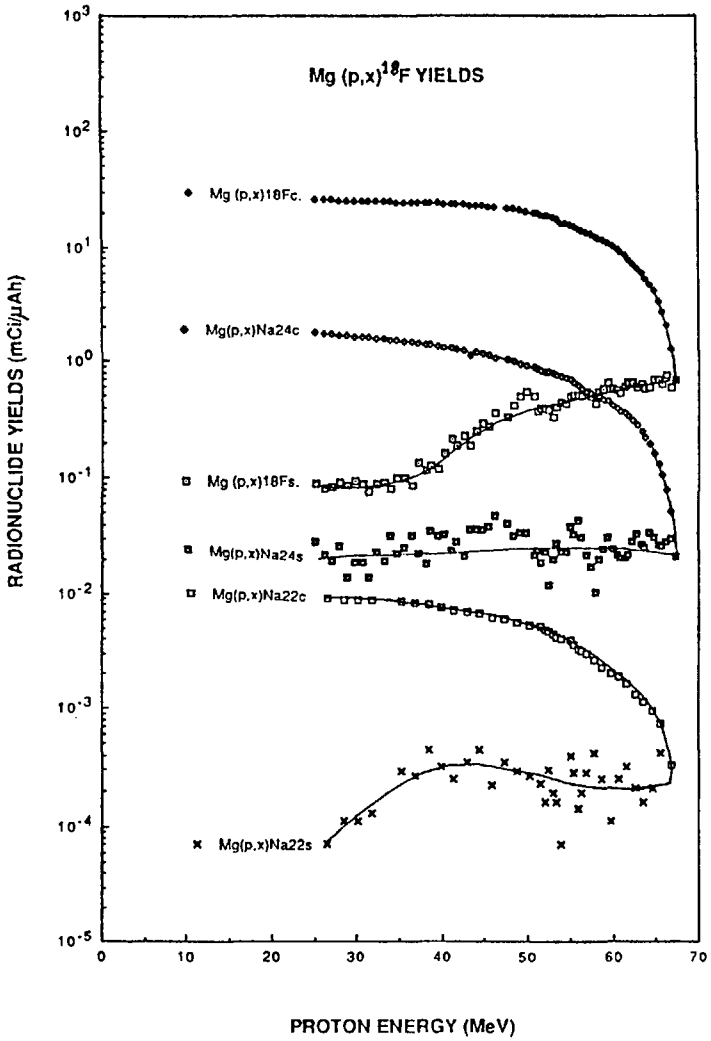
Proton Energy (MeV)	Production Cross Sections (mb)							
	Theoretical values						Experimental values	
	^{18}F	^{18}Ne	Total	^{18}F	^{18}Ne	Total	Total	
Targets:	Na			Al			Na	Al
70.0	13.1	4.8	17.9	2.5	1.2	3.7	24.0	6.9
65.0	14.5	5.4	19.9	1.9	0.7	2.6	26.0	7.2
60.0	16.7	6.8	23.5	1.3	0.3	1.6	30.0	7.0
55.0	17.6	7.2	24.8	0.3	0.1	0.4	36.0	6.0
50.0	17.2	7.1	24.3	0.02	0.0	0.02	40.0	3.3
45.0	13.5	4.6	18.1	0.0	0.0	0.0	50.0	0.7
40.0	8.2	1.6	9.8	0.0	0.0	0.0	40.0	0.2
35.0	1.3	0.1	1.4	0.0	0.0	0.0	20.0	0.1
30.0	0.03	0.0	0.03	0.0	0.0	0.0	5.0	0.0
25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0

(*) Theoretical values were obtained from ALISO code. Experimental values were obtained from fig. 5.



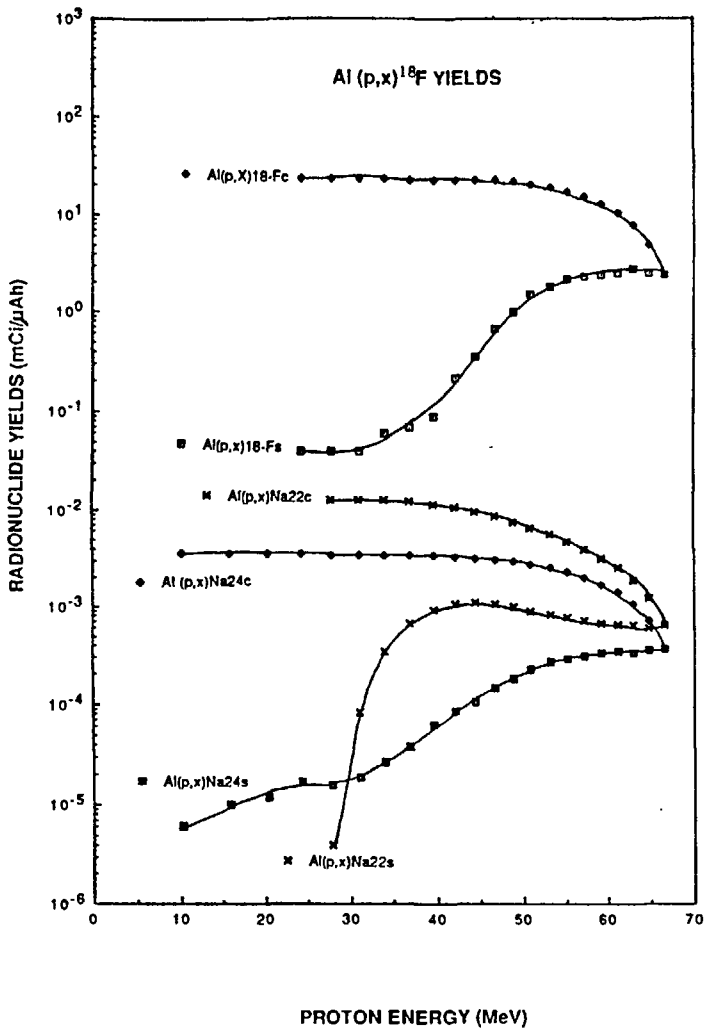
Single (s) thin-target and cumulative (c) yields (mCi/μAh) for the production of 109.77-min ^{18}F, 15.04-h ^{24}Na, and 2.602-a ^{22}Na from Na targets, as a function of proton energy (MeV). The data was eye-fitted for guidance purposes only.

FIGURE 1.



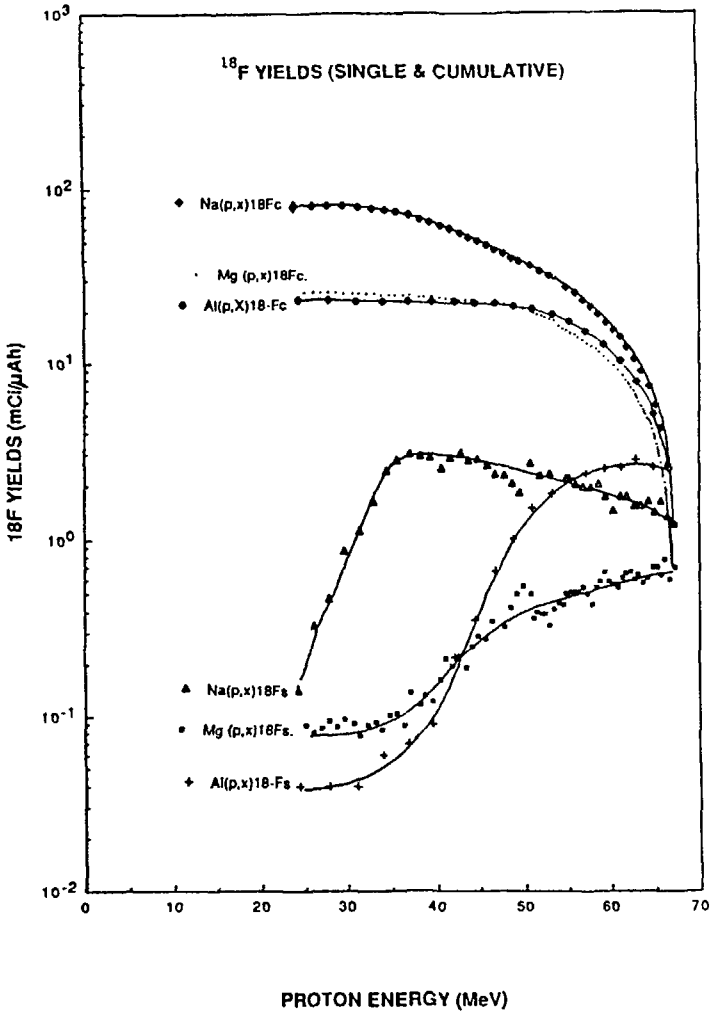
Single (s) thin-target and cumulative (c) yields (mCi/μAh) for the production of 109.77-min ^{18}F, 15.04-h ^{24}Na, and 2.602-a ^{22}Na from Mg targets, as a function of proton energy (MeV). The data was eye-fitted for guidance purposes only.

FIGURE 2.



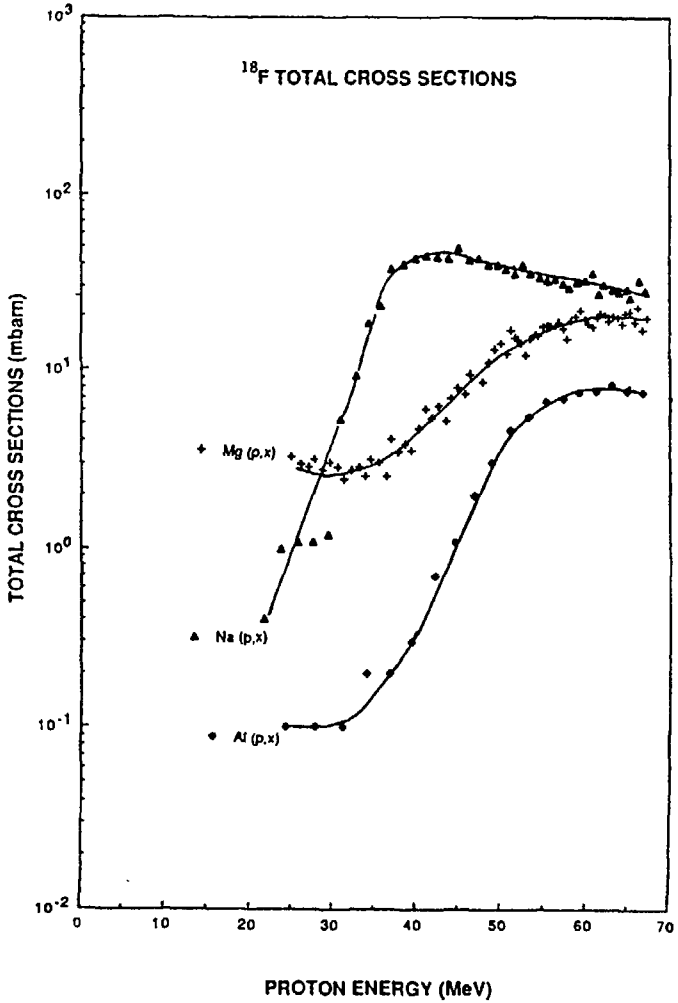
Single (s) thin-target and cumulative (c) yields (mCi/μAh) for the production of 109.77-min ^{18}F, 15.04-h ^{24}Na, and 2.602-a ^{22}Na from Al targets, as a function of proton energy (MeV). The data was eye-fitted for guidance purposes only.

FIGURE 3.



A comparison of ^{18}F yields (single [s] and cumulative [c]) is shown here as a function of proton energy (MeV). Fluorine-18 yields for Na targets are considerably (four fold) better than for Mg and Al targets.

FIGURE 4.



Total cross sections (mbarn) as a function of proton energies (MeV) for the production of ^{18}F from Na, Mg, and Al targets. Each point indicated represents an individual experimental point.

FIGURE 5.

Yttrium-87 Production

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ABSTRACT

In response to the increasing needs for medical radioisotope production, the experimental data for Y-87 production have been compiled. The measurement of excitation functions for Sr(d,xn) reaction were performed by using activation method. The calculation programme of pre-equilibrium emission based on the hybrid model were carried out to determine some excitation functions, which have not been measured before. The yields of Y-87 were estimated for Sr(d,xn), Sr(p,xn) and Rb(α,xn) reactions.

1. Introduction

The Y-87/Sr-87m system is a radionuclide generator with potential use to the medical commurity. Yttrium-87 ($T_{\frac{1}{2}}$=80.3h) decays to Sr-87m state by electron capture and positron emission. Strontium-87m state has a half-life of 2.81h and the 388keV gamma ray is used for imaging with clinical use.

Y-87 can be produced by the Sr(p,xn), Sr(d,xn) and Rb(α,xn) reactions. But only excitation functions for the Sr(p,xn) and Rb(α,xn) have been measured up to now. Therefore the effort was made to determine the excitation functions for the Sr(d,xn) in our laboratory. The measurement of the excitation functions for the reactions has been performed by activation method using stacked-foil technique. Two kinds of strontium samples ($SrCO_3$) with Al backing were used; one was natural, the other enriched in ^{87}Sr.

The measured results were compared with the calculations based on the theory of the evaporation model including pre-equilibrium emission. The cross sections for (p,n) and (p,2n) reactions on ^{86}Sr and ^{87}Sr were also calculated. The result for $^{87}Sr(p,n)$ reaction was compared with the experimental data of ref. (1).

Available experimental data for the Sr(p,xn), Sr(d,xn) and Rb(α,xn) reactions were compiled and compared. The yields of yttrium-87 and the yield ratios Y-87/Y-88 were estimated by the excitation functions for above reactions.

2. Measurement of the Excitation Functions for Sr(d,xn) Reactions

In the present investigation, excitation functions were measured for Sr(d,xn) ^{86}Y, ^{87}Y, ^{88}Y and $^{87}Sr(d,2n)$ reactions in the energy range from 3 to 13 MeV. The measurements were performed by activation method using a stacked-foil technique.

The two kinds of target material used was natural $SrCO_3$ and enriched $SrCO_3$ in ^{87}Sr. The isotopic abundance of the enriched ^{87}Sr target was ^{88}Sr-61%, ^{87}Sr-37.6% and ^{86}Sr-1.4%.

The strontium target foils of thickness range 30-120 $\mu g/cm^2$ were prepared by sputtering method. The target backings is aluminium foils with about 13 mg/cm^2 thick. The thickness of the target foils was determined by Rutherford backscattering method. The error in the thickness was estimated to be about 10%.

The target stacks were exposed to monoenergetic deutron beam. The current intensity of the deutron beam was monitored by a Faraday cup with digital integrator. The energy degredation of the beam by such a target was taken from the work of C.F.Williamson[2].

The irradiation was carried out at the variable cyclotron of IAE with 13 MeV deutron beam (~0.2μA). The duration of the bombardment was about 1 hour.

After bombardment, the radioactivity of each target foil was measured by a Ge(Li) detector-PDP11/34 computer system.

The measured excitation functions for the Sr(d,xn) and $^{87}Sr(d,2n)$ reactions are plotted in Fig. 1. All the nuclear decay data (half-lives, gamma ray energy, branching ratios, etc.) used in cross section calculation were taken from the Table of Isotopes[3]. The estimated error in the measurement of the cross sections was about 15%. These include uncertainties in the estimation of photopeak areas, calibration of the efficiencies of the Ge(Li) detector, determination of the thickness of the target foils, measurement of the intensity of the deutron beam, etc.. Factors not included in the quoted uncertainties are those connected with decay schemes.

The energy spread cause by deutron beam penetrating the target stack was estimated to be within 0.15 MeV.

3. Comparison with Theoretical Calculation

The experimental excitation functions are compared with the theoretical calculations in Fig. 2. The calculations were carried out by an VAX/730 computer with the code HFTT[4].

The calculation program used is based on the theory of pre-equilibrium emission according to the hybrid model[5] [6] and the equilibrium emission based on the evaporation model[7]. The first and second emission particles considered in the nuclear reactions were n, p, t, ^{3}He, d, ^{4}He and γ. The third emission particles considered were n, p and γ. In pre-equilibrium theory, we chose initial exciton configurations of n_0=3 (2p,1h) for proton induced reactions and of n_0=4 (3p,1h) for deutron induced reactions. The Gelbert-Cameron's formulas were used for calculating the energy level density of nuclei. For computation of the inverse cross sections of nuclear reaction, the optical model was used. The optical parameters used in the program were recommended by F.Bechetti et al.[8], Lohr[9] and Mefandden[10].

For the reaction ^{87}Sr(p,n), the calculation is in good agreement with the measured results of J.P.Blaser et al.[1]. For the reaction ^{87}Sr(d,2n), the calculated cross section is about 20% lower than the experiment value in the energy range 10-13 MeV.

4. Comparison of the Yields of the Y-87 Among Three Types of Reactions

The excitation functions for Sr(d,xn), Sr(p,xn) and Rb(α,xn) reactions are shown in Fig. 1, 3 and 4. The ^{87}Y can be produced by the following reactions: ^{86}Sr(d,n), ^{87}Sr(p,n), ^{87}Sr(d,2n), ^{88}Sr(p,2n) and ^{85}Rb(α,2n).

Sr(d,xn) reaction

Fig. 1 shows there are two peaks in the excitation curve of product ^{88}Y. They come from two different reactions which lead to the same product nuclide. The reactions of product ^{87}Y also consist of two reactions. The excitation function of ^{86}Sr(d,n) reaction was gotten from the results for the ^{87}Sr(d,2n) and Sr(d,xn) ^{87}Y reactions. Because the reaction Sr(d,xn)^{87}Y consists of two reactions (^{86}Sr(d,n) and ^{87}Sr(d,2n)).

Sr(p,xn) reaction

The excitation functions for Sr(p,xn) reaction are shown in Fig. 3. The experimental data were obtained from D.R.Sachdev et al.[11], J.P. Blaser et al.[1] and E.A.Skakaun et al[12]. For the ^{87}Sr(p,n) reaction, the excitation curve from J.P.Blaser et al. is disagreement with E.A. Skakaun's result, but is in accord with our calculation. J.P.Blaser's data are very well fitted in with D.R.Sachdev's for ^{88}Y product reaction. The excitation functions for the reactions to produce ^{86}Y nuclide were obtained by summing the cross sections for the ^{86}Sr(p,n), ^{87}Sr(p,2n) and ^{88}Sr(p,3n) reactions at each corresponding energy. The data for the ^{86}Sr(p,n) and ^{87}Sr(p,2n) were obtained by our calculation.

^{85}Rb(α,x) reaction

The data for ^{85}Rb(α,xn) reaction is compiled from Shiro Iwata[13] in the energy range from 10 MeV to 40MeV. The excitation functions for the (α,xn) (x=1-3), (α,α'n) reactions on ^{85}Rb and for ^{87}Rb(α,3n) reaction are shown in Fig. 4.

From the Fig. 1, 3 and 4, we can see that when we got the ^{87}Y radio-isotope which we needed, a lot of other radio-isotope were produced by different reactions, such as ^{85}Y, ^{86}Y, ^{88}Y, ^{89}Y, ^{84}Rb and other radioactive impurity ^{90}Y which is invisible on the gamma spectrum. In view of clinical usefulness, the radioactive impurity should be controlled strictly. Some of impure nuclide (relative to ^{87}Y) can be purified by a chemical separation. But most of the yttrium isotopes can't be separated by this way. Therefore, to get high yield of ^{87}Y and low impurity, the best way is to control the radioactive impurity in the promising reactions through selection of different kinds of target nuclei, incident particles and incident energy.

Because of decreasing the yield ratio Y-87/Y-88 in the parent, the quantity of radioactive nuclide ^{87}Sr is decreased and the chemical poisoning of Sr increased. Breakthrough of the parent increases patient exposure and degrades image quality, especially for radioactive impurity of Y-88. The yield of Y-87 and yield ratio Y-87/Y-88 were estimated. All of them are listed in the table 1. The results are based on the excitation functions of the corresponding reactions in Fig. 1, 3 and 4.

Conclusion

From the table 1, it can be seen that if the natural elements were used as the target to produce ^{87}Y radio-isotope, the highest yield can be gotten by the Sr(p,xn) reactions, with the lowest radioactive impurity by the Rb(α,xn) reactions (exclude the β^- activity of ^{90}Y). If the target of enriched ^{86}Sr or ^{87}Sr will be used to get high yield of ^{87}Y nuclide, two reactions can be considered. One is $^{87}Sr(p,n)$ with 15 MeV incident proton, the other is $^{86}Sr(d,n)$ with deutron energy 13 MeV. Almost no radioactive impurity will be produce in these reactions. But it's expensive.

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Table 1 Comparison of ^{87}Y yield among different reactions

Reaction	(p,xn)	(d,xn)	(α,xn)	(p,n)	(d,n)
Target	Natural Sr	Natural Sr	Natural Rb	^{87}Sr	^{86}Sr
Energy (MeV)	35--15	15--5	35--15	15--5	13--5
Thickness (mg/cm^2)	1600	254	148	400	92
Average cross section (^{87}Y) (mb)	560	80.7	367	439	542
Yield (^{87}Y) (Ci/ A h)	6500	150	200	1300	750
Yield ratio ($^{87}Y/^{88}Y$)	67	7.7	71		
Kinds of impurity	$^{85,86,87}Y$, ^{84}Rb	$^{86,88}Y$	$^{86,88,90}Y$, ^{84}Rb		

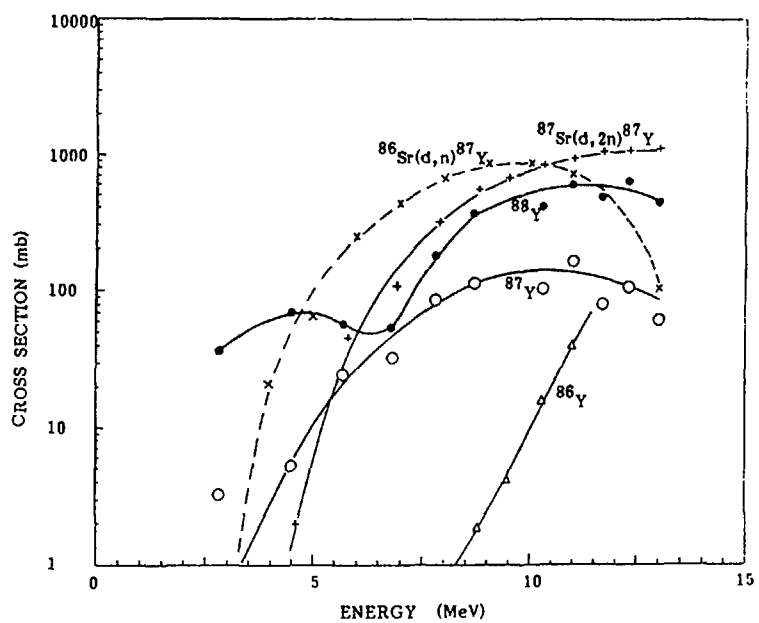

Fig. 1 Excitation functions for Sr(d,xn) reactions.

- ● $Sr(d,xn)^{88}Y$ — $^{87}Sr(d,n) + ^{88}Sr(d,2n)$
- ○ $Sr(d,xn)^{87}Y$ — $^{86}Sr(d,n) + ^{87}Sr(d,2n)$
- △ $Sr(d,xn)^{86}Y$ — $^{86}Sr(d,2n)$
- \+ $^{87}Sr(d,2n)^{87}Y$ reaction
- × $^{86}Sr(d,n)^{87}Y$ reaction

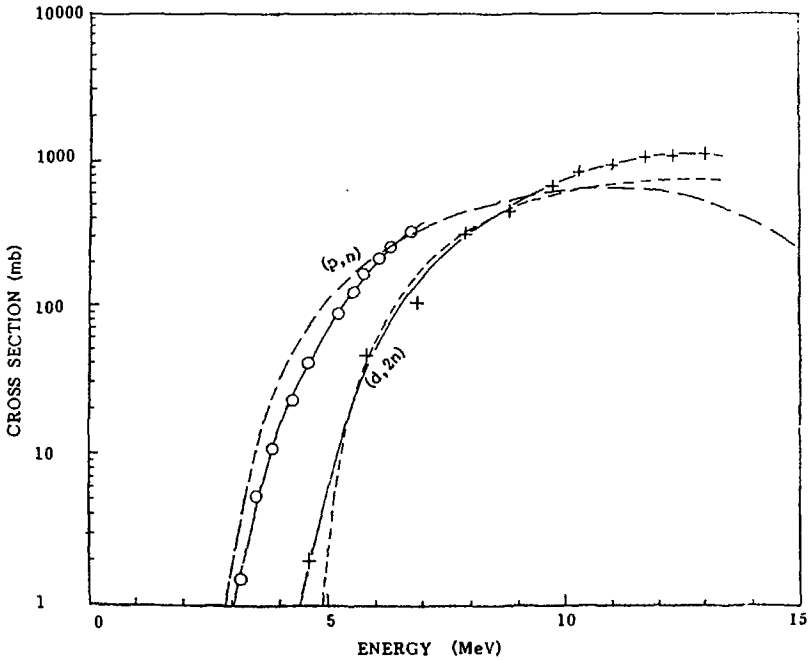

Fig. 2 Comparison of experimental and theoretical results for the excitation functions of ^{87}Sr(p,n) and ^{87}Sr(d,2n).

○ ^{87}Sr(p,n)
\+ ^{87}Sr(d,2n)
—— Exp.
- - - Theo.

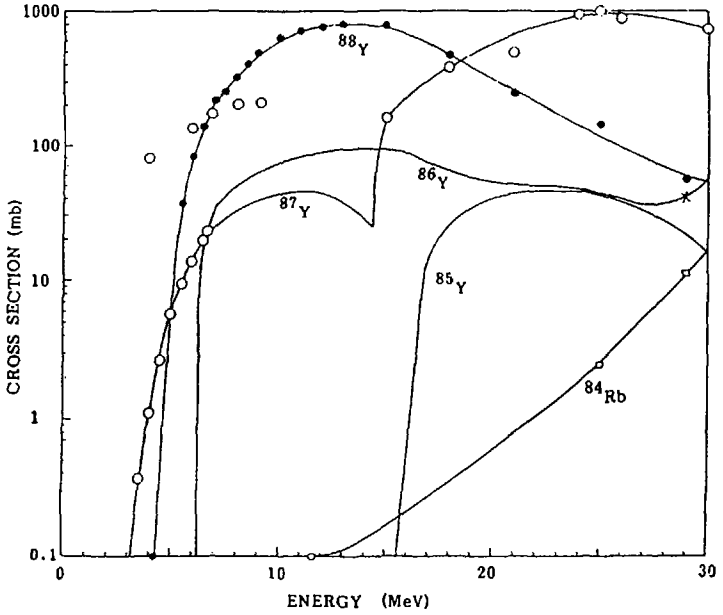

Fig. 3 Experimental and theoretical results for Sr(p,xn) reactions.

Exp.
• ^{88}Y —— ^{88}Sr(p,n)
○ ^{87}Y —— ^{87}Sr(p,n) + ^{88}Sr(p,2n)
□ ^{84}Rb —— ^{88}Sr(p,αn)
× ^{86}Y —— ^{88}Sr(p,3n)

Theo.
^{86}Y —— ^{86}Sr(p,n) + ^{87}Sr(p,2n)
^{85}Y —— ^{86}Sr(p,2n)

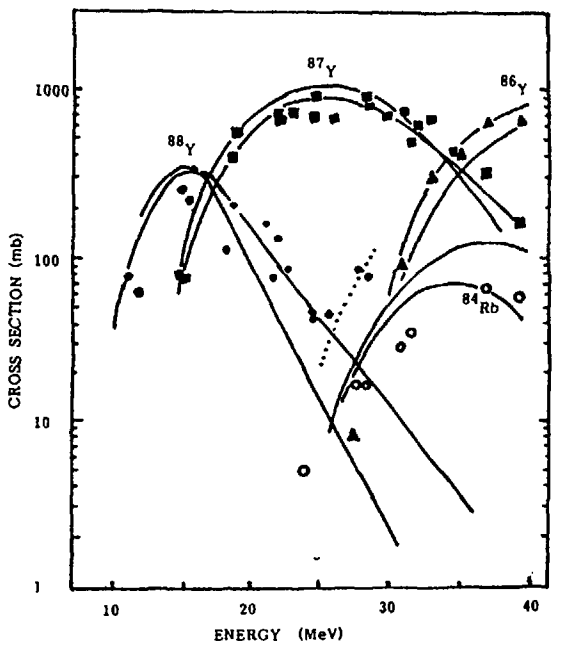

Fig. 4 The excitation functions for induced reactions on ^{85}Rb[15].

• ^{85}Rb(α,n) + ^{87}Rb(α,3n)
■ ^{85}Rb(α,2n)
▲ ^{85}Rb(α,3n)
○ ^{85}Rb(α,α'n)
—— Calculated value

Production of medical used radioisotopes with the triton beam of a compact cyclotron

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Abstract

Despite of the small e/m value triton acceleration with a compact cyclotron is used for the production of radioisotopes because of the high (t,p) cross section and the high beam current of the machine. The tritium handling system, the production of ^{28}Mg and the ^{42}Ar-^{42}K radioisotope generator are described.

Introduction

Compared with the other light and heavy ions, tritons are very infrequently used for the production of radioisotopes. At the moment our compact cyclotron is the only used for that purpose. Reasons are the strict regulations about radioactivity to avoid contamination of the staff and of the vicinity of the laboratory. Therefore, a very safe system had to be constructed which gives the possibility to accelerate tritons at the AEG-Compact-Cyclotron in Munich (ref. 1). The design of this system will be described in detail in section 2.

Normally a cyclotron is not well suited for triton acceleration due to the small e/m-value in our case we obtain only 7 MeV tritons instead of 28 MeV $^{3}He^{2+}$. But this disadvantage is overcompensated by several other aspects. Firstly the cyclotron is not used for experiments in nuclear physics but mainly for the production of radioactive sources necessary in many fields of science. It is more easy to secure an uninterrupted supply of radioisotopes to other laboratories with such a "service" machine. Secondly, the low energy of the tritons has on the other hand an advantage, too. The cyclotron is frequently used to accelerate high intensity proton beams with more than 500 uA to an energy of 22 MeV. This requires an essentially higher power rating of the machine than during triton acceleration. However, the machine runs very reliable for triton acceleration because of less rf power required. Furthermore, the low triton energy prevents nuclear reactions in the target backing.

The triton acceleration was started first under provisional permission of the Bavarian Ministery of Environmental Affairs. Since July 1978 we operate our system under definite permission (ref. 2). Till now we did not have any major accident.

2. The tritium handling systems

The principle of the design for the tritium handling system was:

a) to avoid the storage of gaseous tritium
b) to get a closed vacuum pumping system with no connection to the environment during triton acceleration.

a: The tritium storage system

In the compact cyclotron the ions are accelerated from an internal ion source. For a stable low-pressure gas discharge a gas pressure of approximately 10^{-2} Torr in the ion source is necessary. This corresponds in our case to a pressure of 10^{-5} Torr in the cyclotron vacuum chamber and to about 1 Torr in the buffer vessel of the gas supply. For economical and security reasons this pressure is produced by a carrier gas to which tritium is only admixed in a ratio of 1 : 100.

Therefore, a tritium partial pressure of 10^{-2} Torr in the buffer vessel is sufficient for triton beam currents up to some 10 uA. This necessary amount of tritium is delivered by the new tritium storage consisting of two SORB-AC getter pumps GP 50 (S.A.E.S.-Getters, S.p.a., Milan, Italy). The tritium is stored in these pumps in a very safe way as a "solid solution" (ref. 3). The design of this pump-type is shown in fig. 1. The getter material consists of a 84% Zr - 16% Al alloy pressed onto metal strips, which are folded in concertina style to form a cylindrical cartridge with maximum surface area and getter efficiency. As the pumping speed (l/s) and the maximum sorption capacity (Torr l) are proportional to the surface area, several sizes of cartridge getter pumps from 50 l/s (GP 50) to 500 l/s (GP 500) are available. For a given surface area of the getter material, a well-defined partial pressure of hydrogen corresponds in the equilibrium state to the quantity of hydrogen absorbed in the getter. This partial pressure is strongly dependent on the temperature of the getter as shown in fig. 2. It can be calculated from the semi-empirical formula: (ref. 4) $\log p = 4.4 + 2 \log q - 7000/T$, where p denotes the partial pressure of hydrogen in Torr, q the concentration of absorbed hydrogen in Torr, q the concentration of absorbed hydrogen in the getter in Torr l g^{-1} and T the absolute temperature in K.

Because of this physical behaviour SORB-AC getter pumps can be used as a temperature-controlled reversible reservoir, where tritium is pumped at low temperatures and released at high temperatures.
In our case e.g. (see fig. 2) for an obsorbed quantity of 1500 Ci, equivalent to 213 Torr l in each cartridge, the partial pressure is theoretically only 10^{-17} Torr at room temperature, but will rise to 10^{-2} Torr at $T_1 = 575^{o}C$. When tritons are accelerated, the quantity of absorbed tritium diminishes. To keep, however, the partial pressure of tritium constant at 10^{-2}Torr, the temperature must slowly be raised above $575^{o}C$ in the course of time. The maximum allowed temperature of the getter is $800^{o}C$. If this temperature T_2 is reached the partial pressure of tritium will no longer be constant but will decrease. For security reasons the getter cartridge must be replaced by a new one. The amount of tritium still gettered is about 29 Torr l (equivalent to 38 cm^3 or to 102 Ci in each cartridge) for this pump type. The cartridge must be processed as radioactive waste. The getter cartridge is installed on ceramic insulators in a stainless steel vacuum vessel (see fig. 1). The cartridge encircles the concentric heater element. The temperature of the getter is directly measured by thermocouples. Tritium penetration through the walls of the vacuum vessel is avoided by a water-cooled jacket. This prevents simultaneously that the power of 0.05 W absorbed in the cartridge due to the radioactive decay of tritium (1500 Ci, $E_\beta = 5.6$ keV) raises the temperature of the cartridge to more than about $40^{o}C$. Therefore, no danger of releasing tritium by self-heating exists.

b. The vacuum system

The original vacuum system of the compact cyclotron consists of two oil diffusion pumps and of a common roughing pump. Pumping the tritiated rest gas of the cyclotron vacuum chamber with this set-up would surely contaminate the pump oil. This requires a tritium purification fraction by some orders of magnitude. Therefore, we have installed a large sputter-ion pump to be used when tritium is accelerated. The great advantage of this closed system, built up in UHV-technique, is that no gas exhaust exists and that the tritium gas which is not ionized is safely trapped in the sputter-ion pump (see fig. 3). This pump (ULVAC PST-125 A) is directly connected to the vacuum chamber of the cyclotron by a bellow-sealed valve, while the diffusion pumps are

disconnected by two dis-valves. The pumping speed of the sputter-ion pump is 4500 l/s for hydrogen and 2000 l/s for nitrogen. The lifetime of the pump is about 4000h at a pressure of 10^{-5} Torr. The radioisotopes produced with the triton beam have, in general, lifetimes of some hours for one charge. That means in the lifetime of the sputter-ion pump one can produce 1000 charges of radioisotopes. A recycling of the trapped tritium does not seem to be reasonable comparing the price of the tritium, which is now about 1 Dollar/Ci, with the price of the mechanical set-up and with the security risks of such a recycling procedure.

In spite of these precautions, there remains nevertheless a contamination of tritium on all surfaces inside the cyclotron. If the vacuum chamber of the cyclotron must be opened or ventilated, the tritium from the walls partially exchanges with the hydrogen in the air. If it is evacuated again, a measurable amount of tritium is released to the environment. Therefore, (since September 1979) the exhausts of all roughing pumps are connected to a hydrogen-tight gas-storage balloon with a volume of 5 m^3. The stored contaminated exhaust gas is cleaned in amounts of 400 l for some hours in an oxidation furnace. This copper-oxide furnace, type T2CT-150 from UKEM, W.-Germany, oxidizes the tritium gas catalytically to tritium water, which is afterwards absorbed in a molecular sieve.

3. Production of radioisotopes

The (t,p) cross section for the radioisotope production is rather high, which compensates the low energy of the triton beam in a compact cyclotron. The two radioisotopes ^{28}Mg and ^{42}Ar are produced via this reaction.

3.1 Magnesium-28

$$^{26}Mg\ (t,p)^{28}Mg\ (21.3h/\beta^-)^{28}Al\ (22m/\beta^-)^{28}Si$$

The target assembly used for the production of ^{28}Mg is designed for beam currents up to 30 uA, provided there is a good thermal contact between the copper backing and the target material, which for the high intensities must have a good thermal conductivity. The ^{26}Mg (88%) metal is evaporated onto the front of goldplated cylindrical copper rods of 9 mm diameter, which are water-cooled from inside. The gold layer is thick enough to stop the tritons after penetrating the thin target material, but its high Coulomb barrier prevents nuclear reactions with the tritons. Furthermore neither the copper can go into solution, when the irradiated target is chemically dissolved with acids, nor can the stopped tritons come out. A beam of 30 uA corresponds to an accelerated quantity of tritium of 33 mCi/h. An angle of incidence of 5^o between the beam and the target surface increases the beam spot to an area of about 3x10 mm^2, which improves the cooling effect. The specific activity is not influenced as the target thickness can be smaller in this case.

A target thickness of 5 mg/cm^2 is chosen. The thick target yield of the reaction is up to 110 uCi (4 MBq)/uA

The yield is more depending on the conditions of the targets than of the irradiation. Up to 3 Ci (i.e. 1 Ci/mg) could be produced with one target. Besides in West Germany and Berlin also in the United Kingdom in vitro experiments are done with our ^{28}Mg.

3.2 The ^{42}Ar - ^{42}K radioisotope generator

$$^{40}Ar(t,p)^{42}Ar(33\ a/\beta^-)\ ^{42}K(12.4h/\beta^-)^{42}Ca$$

With a half-life of 33 years a ^{42}Ar - ^{42}K generator in principle could be used for 100 years. Fig. 4 shows the argon gas target. It consists of a four blinds flange for the beam correction and a stainless steel cylinder of 120 mm length and 100 mm diameter. In front is a window of 45 x 5 mm for the beam entry. It is closed with 2 molybdenum or tantalum foil of 5 um thickness.

The beam current is 20 uA, the thick target yield is 5 n Ci (185 Bq)/uAh. During one long term irradiation up to 12 uCi could be produced. After irradiation the Argon is pumped in a so-called "cow", which then is shipped to the users (fig. 5). In this cow the ^{42}Ar and ^{42}K can be separated electrostatically. The size of the cow is depending on the activity which is wanted. To reduce diffusion of the argon gas through the valve and septa it has to be kept at normal pressure.

At the moment such generators are used for in vitro experiments in Germany, Spain, Denmark and Japan. In Japan it is also used in schools to demonstrate the handling of open radioactivity. At our University one experiment is part of a curriculum for students.
One experiment which was made in our institute was the determination of the influence of antimicine A on the potassium transport in erythrocytes (ref. 5).

Conclusion

On our opinion the production of medical used radioisotopes with the triton beam of a compact cyclotron is useful, even with the low energy one can. For extended production calculation codes for low energy, particles could be useful. There exists also a need for experimental data. Discussing the data requirements for medical radioisotope production one should therefore not only think about the extension of excitation functions and codes for very high energy particles, but one should not forget that there still exist data requirements for low energy projectiles.

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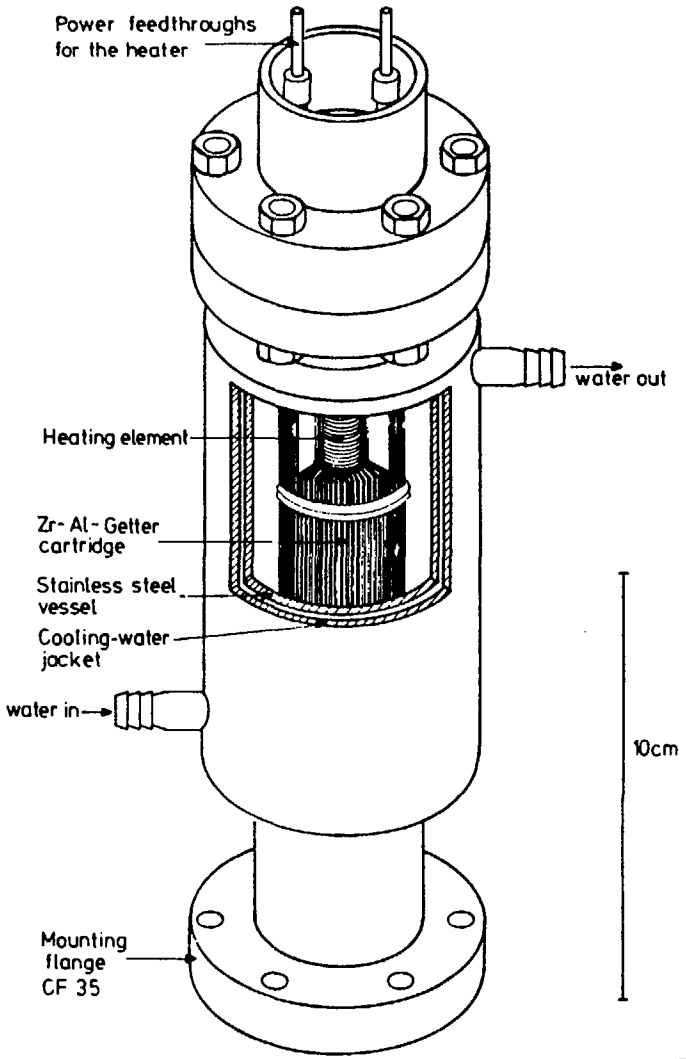

Fig. 1.

Mechanical set-up of the S.A.E.S. getter pump GP 50

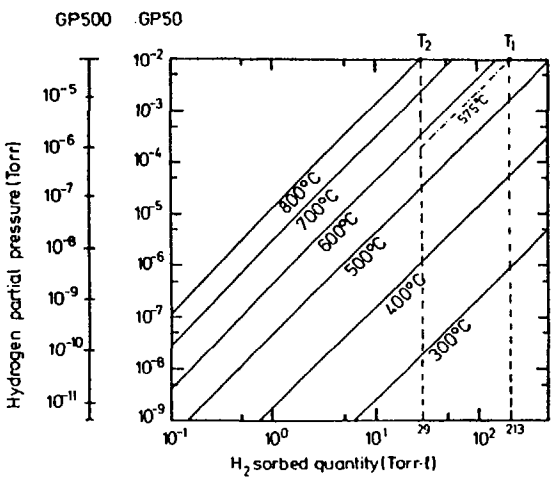

Fig. 2.

Hydrogen partial pressure plotted vs the absorbed quantity of hydrogen for different temperatures. The two scales correspond to the getter pump types GP 50 and GP 500, respectively.

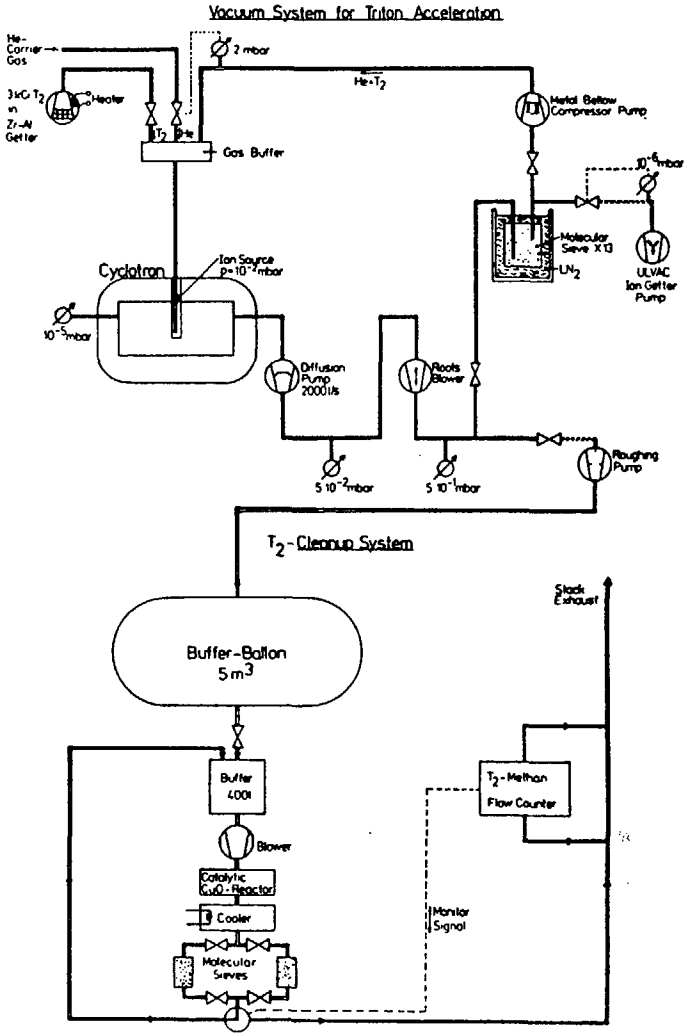

Fig. 3.

The tritium handling system

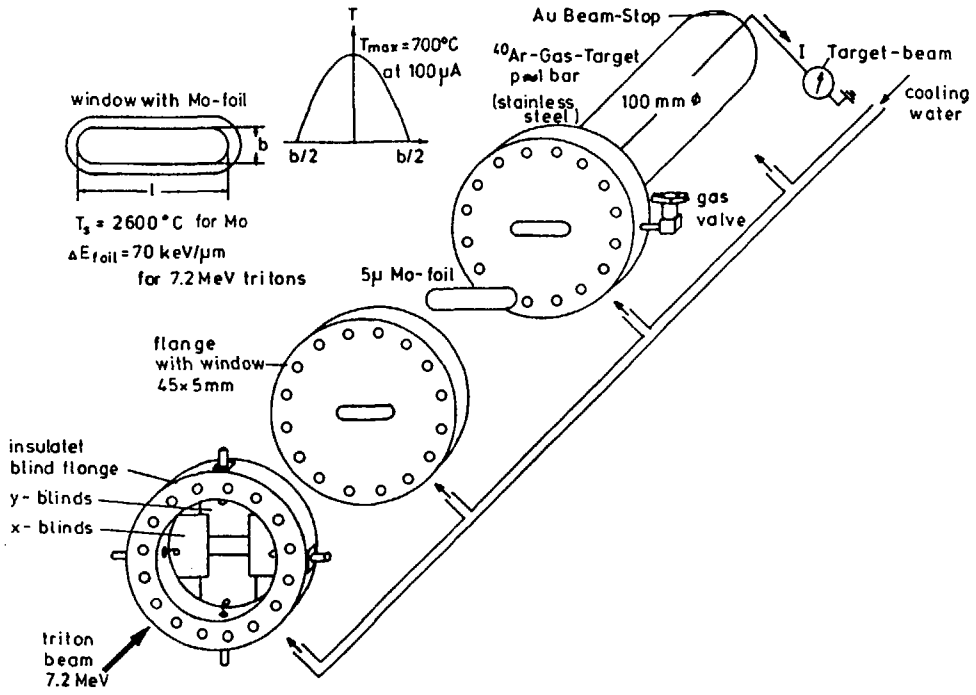

Fig. 4.

The Argon gas target

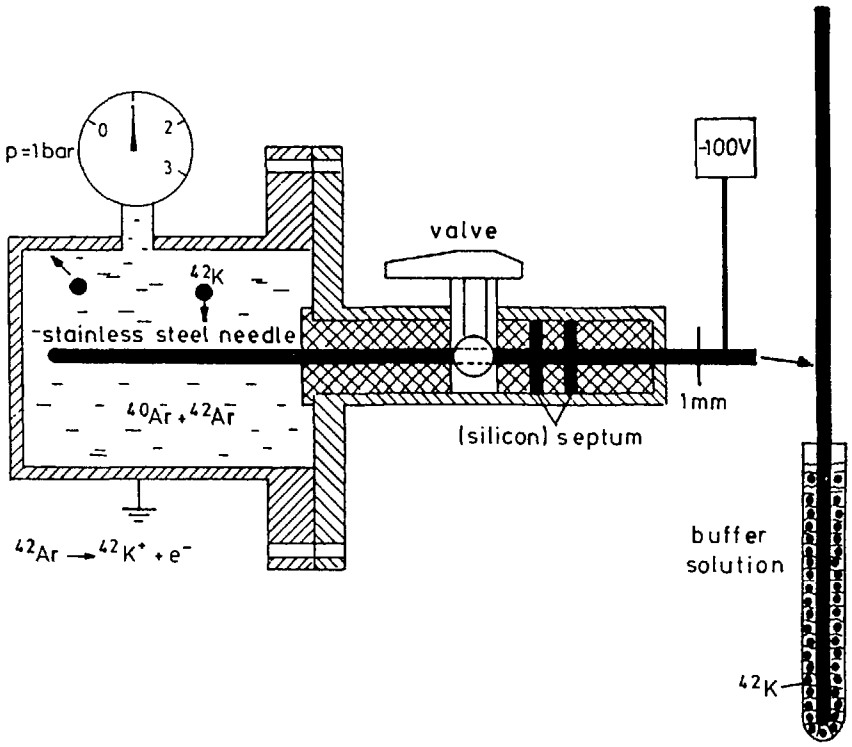

Fig. 5.

Electrostatic separation of ^{42}K and ^{42}Ar
"Argon - 42 cow"

SPALLATION PRODUCED RADIOISOTOPES FOR NUCLEAR MEDICAL APPLICATION

* * *

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SUMMARY

Spallation reaction opens new additional possibilities for production of a number of medical useful isotopes. In some cases all the present world demand is produced through spallation. Because of the high transmission of targetmaterials for medium or high energy protons lower cross-sections may be more than compensated by using massive targets. The unspecific nuclear reaction as well as the radiochemical processing of such massive targets leed to several difficulties. New ways for processing of large spallation targets are required. The possibilities of modern ISOL-techniques (ISOL = Isotope Separator On-line" for the production of medical useful radio-isotopes will be discussed in some detail. Corresponding cross-section data are reviewed and discussed in relation to physico-chemical data requirements. In detail the following radio-isotopes will be discussed:
^{81}Rb, ^{82}Sr, ^{123}I, ^{167}Tm and ^{211}At.

INTRODUCTION

It is well known, that spallation reaction is the most convinient way to produce very neutron-deficient nuclei far from the line of beta-stability /1-3/. The use of intense beams of high energy protons has been also recognized and exploited for some time for the production of neutron deficient radioisotopes for practical application /4-11/. The main advantage of beams in the 0.5 to 1 GeV range lies at present in high product output through an ability to penetrate and induce nuclear reactions in target materials having thicknesses on the order of hundreds gramms per cm^2. The large number of target atoms can more than compensate for the generally low reaction cross sections (order of 10^{-30} m^2 or 10 mb) compared to the cross sections often associated with lower energy reactions used in more conventional ways for isotope production.

In interactions of high energy protons with heavy target elements three main typs of nuclear reactions occure: spallation, fission and fragmentation (see fig.1 taken from /16/).For cross-section or yield calculations for the spallation still analytical methods based on the work of RUDSTAM /12/ are used. RUDSTAM observed, that the cross-section for isodiapheric nuclei grow with increasing mass-number or oposit decreases homogeneously with growing mass deficiet. Consequently he proposed an empirical exponential equation, which was than modified for special applications /13-15/.

Cross-sections for spallation reaction products have been discussed at the IAEA Consultants Meeting in Vienne, 13-15 April 1981 /20/. In generall measurements of spallation cross-sections fall within a factor of approximately 2 of the value predicted by RUDSTAM's empirical systematics /12/ which seems to be sufficient for the moment. Optimization of target- and separation techniques are of similar importance. It is the aim of this paper to discuss the production of medical isotopes via spallation as a complex problem of the nuclear reaction and chemical or physical principles of separation techniques.

The long range of the high energy protons permits the simultaneous irradiation of stacked thick targets as well as the use of a single massive target. The advantage is that several radioisotopes are available in both cases simultaneously. But this advatage is also an disadvantage because of the formation of isotopic impurities. This problem must be handled through optimized choices of irradiation and decay periods as demonstrated in the case of 123-I via 123-Xe /17,18/. The plethora of waste and by-product radioelements to be dealt with are other complicating factors. Nevertheless practically all the present world supply of 82-Sr and 67-Cu and good fractions of 127-Xe, 109-Cd and 68-Ge are produced via spallation reaction /6,7,11, 19/. It is our suggestion, that new separation techniques could solve some of the problems and open possibilities to produce valuable spallation radioisotopes in a more sufficient way.

To day new rapid separation methods based on thermochemical and physical principles allow radioactive nuclei of allmost all elements to be contineously transferred from an accelerator irradiated target into an ion beam. These techniques often referred to as target ion-source system have in the last 20 years turned on-line mass separators into the most efficient tool for production and study not only of nuclei far from stability but radioactive nuclei in general /23/. The principle of such an ISOL-system is shown in fig.2. For more generall information see /1-3/.

The production, transport and separation processes in such an integrated ISOL-system can be divided into the following main steps:

i. Formation of the products in interaction of an intense proton beam of around 700 MeV
ii. Diffusion of the product nuclei from the interior to the target surface
iii. Desorption from the surface
iv. transport of the product to an ion-source
v. Ionization of the product
vi. Mass-separation of the products.

For a complete description of the processes we need to know about the following data (others than nuclear data):

- Diffusion coefficients
- Adsorption enthalpies
- Ionization behaviour.

HIGH TEMPERATURE DIFFUSION

The solution of the second FICK law

$$\frac{dc}{dt} = D * \frac{d^2c}{dx^2} \qquad (1)$$

$$F(\%) = 100 - \frac{800}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2 \pi^2 D t}{d^2}\right] \qquad (2)$$

describes the relation of fractional release (F) of a given nuclear reaction product, the diffusion coefficient (D) and the target-foil thickness (d) /24/. This equation (2) is applicable for the special sample conditions: foils or plates where the foil-thickness d is small compared to the length and width ($d >> a \approx b$) and with homogeneous distribution of the diffusing particles throughout the matrix. The experimental value F can be transformed into diffusion coefficients using the tables of ZIMEN /25/. The activation energy E_a for the diffusion process can be obtained from an ARRHENIUS plot according equ.(3).

$$D = D_o \exp\frac{E_a}{RT} \qquad (3)$$

where R is the gas-constant.

Systematical studies have been performed in the following manner: target foils of refractory metals were labelled homogeneously with radio tracers by irradiating them with 660 MeV protons. Sampels of the irradiated foils were annealed in high vacuum at high temperatures. The samples were analyzed before and after heating by means of gamma-spectroscopy for determination of the fractional release of spallation reaction products. The results are published for the following target elements: Ti /26,33/, Zr /26,27/, Nb /28/, Mo /29/, Hf /30/, Ta /31/, W /32/, Re /33/, Ir /33/, Th /33/. For illustration a few results are presented in figs.3-6.

The diffusion release studies may be summarized in the following way:

i. In a given host metal of the IV B , V B or VI B group of the periodic table the diffusion coefficients for trace elements grow in the following sequence:

$$D_{Ia} < D_{IIa} < D_{IIIa}.$$

For example Y diffuses faster than Sr, which is faster than Rb (see fig.3). The reason for this sequence is the decreasing radius of the diffusing particles.

ii. The diffusion coefficient for a given trace element decreases for different host metals in the following sequence:

$$D^{IVB} > D^{VB} > D^{VIB}.$$

For example Y diffuses fastest in Zr and in Nb faster than in Mo. Compare figs.3 and 5. The reason for this effect is the growing lettice density of the host metals.

iii. In a given host metal the elements of one group of the periodic table diffuses according to growing atomic masses: Sr diffuses faster than Ba in Ta (see fig.6).

iv. From the systematical study one can evaluate, that all rare earth elements diffuse in metal matrixes as M^{3+}-ions, the II A-elements as M^{2+}, the alkaline elments as M^{+} and the nobel gases as neutrals (see fig.6 and fig.3).

In generall one can conclude that solid phase diffusion processes very often are fast in order to use refractory metals as high temperature targets. A large number of other refractory materials such as metaloxides, borides, carbides as well as molten metals and alloys has been investigated to develope suitable targetsystems for ISOLDE (review papers see /61,60,44/).

SURFACE EFFECTS

In our release studies we found that in Ta the diffusion of the rare earth elements is more rapid than of Ba followed by Cs. For the desorption from the surface the sequence is reverse with Cs being fastest followed by Ba, lanthanoides and Hf. Thus in a Ta-powder target the rare earth elements will be delayed compared to Cs and Ba due to the large total surface. Consequently from a Ta-foil target with optimized foil thickness the rare earth elements will be released more rapidly because the surface is diminished. The surface adsorption behaviour or in other therms the adsorption enthalpies play an important role in the release of nuclear reaction products from a target as well as for the transport of the products in the gas phase.

Desorption studies for rare earth elements have been performed in a similar way as the release studies /34/. Fig.7 illustrates the possibilities to use differences in the adsorption enthalpies for thermochromatographic separations.

A systematical study of the adsorption of trace metals at metallic surfaces hase recently been published by ROESCH and EICHLER /35/. The wide variation of the surface material, the composition of the used carrier gases , variation of the gas preasure and temperature opens the wide range of separation techniques starting from gaschromatography over gasthermochromatography and thermochromatography to vacuum thermochromatography.

IONIZATION

A selective ionization is a modern radiochemical separation technique. For the production of radioisotopes via spallation the following ion-source principles are suitable to be operated in an integrated target ion-source system:

i. Positive surface ionization ion-source with Ta-ionizer kept at 1300 K for selective ionization of the alkaline elements K, Rb, Cs and Fr /36/. The ionization efficiency is of the order of 90 %.

ii. Positive surface ionization ion-source with W-ionizer (or Re) at high temperatures (2700-3000 K) for ionizing the lanthanoides, In, Ga, Sc, Al, Ca, Sr, Ba, Li, Na and Tl. The ionization efficiency varies from a few % up to 80 % /36, 37, 38/.

iii. Negative surface ionization ion-source with LaB_6-ionizer for selective ionization of Cl, Br, I and At. Ionization efficiences of up to 40 % have been obtained /36,39/.

iv. The plasma discharge ion-source with cooled line at 300 K and ionization temperatures around 1300 K is used for selective ionization of nobel gases. Efficiences achieved for He, Ar, Kr, Xe and Rn are 0.5 %, 2 %, 5 %, 15 %, 30 % and 40 % respectively /36/. A similar source with a cooled line kept at 700 K is used to ionize the volatile elements of the group IIB Zn, Cd and Hg with efficiences of 10 - 60 % /36/.

v. A high temperature version of the plasma discharge ion-source (line at 2200 K) is intended to ionize the less volatile elements from group IB, III, IV and V. This ion-source can be used in conjunction with CF_4 to form volatile fluorides of the mentioned elements /36/.

CHEMICAL SELECTIVITY

As mentioned the product mixture of a massive target irradiated with protons with E_p 0.5 GeV is rather complex. The difficulties to handle such targets and product mixtures can be compared with the fission product mixture in isotope production plants only. Nevertheless chemical selectivity can be obtained using the above mentioned techniques by one or several of the following means:

i. Selective release from the target (Sr from Zr /40/).

ii. Selective adsorption of unwanted species at suitable surfaces (selctive release of Yb from Ta-powder /33/) or selective transport of the required product (52-Fe from Ni /41/).

iii. Selective ionization

iv. Mass-separation of molecular side bands (iodine as AlI^+-particles /36/). Isobaric separations using differences in the adsorption enthalpies /42/.

ISOL-TECHNIQUE FOR PRODUCTION OF MEDICAL ISOTOPES VIA SPALLATION

In this chapter we like to illustrate the possibilities of the discussed techniques for the production of some of the most important medical radioisotopes via spallation route.

^{81}Rb

Because of the short halflife there is no much sense to produce 81-Rb via spallation, but the isotope separator opens the way to produce a new type of 81-Rb-81m-Kr-generator. 81-Rb is best produced at ISOLDE using a Nb-powder target with yields of 3.8 * 10^{10} atoms per second for 1 ,uA proton beam current (fig.9 /44/). This production rate corresponds to 1.6 MBq/,uAs (or 20 mCi in 7.7 minutes collection time for 1 ,uA proton beam current). By implanting the 81-Rb$^+$-ions into mylar foils (or other plastic material like polyethylene etc.) an implantation type of 81-Rb-81m-Kr-generator is obtained. The 81m-Kr can be eluted nearly quantitatively by blowing air over the implanted Rb-source as well as by elution with isotonic saline solution suitable for direct infusion /43/. No 81m-Kr-elution will be achieved by using metallic foils as implantation backing. The 81-Rb break through is as low as in conventional 81-Rb-81m-Kr-generator systems. The implantation type generator could be realized of extremly small size since for an implantation density of 10^{14} atoms/cm^2 less then 0.5 cm^2 foil area is required to make a 800 MBq (20 mCi) generator.

^{82}Sr

Recently the complete problems about 82-Sr-82-Rb-generators have been published /45/. The cross-section for the formation of 82-Sr in Mo irradiated with 800 MeV protons is $(2.3 \pm 0.1)*10^{-30}$ m^2 (23 mb) and for 85-Sr $(4.8 \pm 0.7)*10^{-30}$ m^2 (43 mb) /46/ (tab.1). The radiochemical procedure hase been modified several times /47,48,48/. High dose rates of the irradiated targets (10^7 R/h in 1 cm distance /48/), large amounts of process solutions and unsatisfied purity of the final 82-Sr-preparation were the main problems in the wet radichemical process /48,49/. The isotopic byproduct 85-Sr remains still a serious problem. At EOB an average isotopic ratio 82/85-Sr of only 1.0 to 1.2 is obtained depending on irradiation time. During the clinical use of the generator the 85-Sr grows up to an excess of a few 100 % compared to the 82-Sr activity. It was allready proposed to solve this problem by using an isotope separator /48/.

We recommend to use additional ISOL-target technique. From a 50 g/cm^2 Zr-foil target (foil-thickness up to 0.5 mm) the Sr is released rather selective at 1750 K (fig.3). A high temperature surface ionization ion-source could give an ionization yield of better then 50 %. At the collector of an isotope separator pure 82-Sr and 85-Sr could be collected. The cross-contamination for routine practical use is almost less then 0.1 % in this mass region. Recent studies at CERN demonstrated, that a Zr-foil target could withstand a well focused proton beam of 100 ,uA /50/. It is expected to obtain 10^{10} atoms 82-Sr per 1 ,uAs or 10^{10} Bq/1000,uAh (10h, 100 ,uA). The advantage of this technology is first the high isotopic purity, secondly practically no liquid waste is produced. The disadvantage is that no other product as 77-Br or 88-Y are available simultaneously from the same target.

^{123}I

Special interest was directed to the production of radioxenon via spallation /18,20,51/. It has been demonstrated, that by optimized choice of irradiation and decay periods rather pure 123-I could be obtained. Also important was the possibility to produce 125-I and 127-Xe simultaneously. From a 175 g CsCl-target after 4 hour irradiation and 4 hour grow in period for 123-I via 123-Xe decay 850 mCi 123-I with 0.4 % 125-I contamination is obtained /52/. The 127-Xe produced via spallation at TRIUMF from a 0.8 cm thick CsCl-pellet contains 15 % of 129m-Xe and 12 % 131m-Xe /11/. Cross-section data are summerized in tab.1.

The 125-I contamination in spallation produced 123-I preparations presently is higher than those for the (p,5n)-production route. One possibility to solve this problem is the application of ISOL-technique. From a molten La-target kept at 1770 K Cs is released fast and transported to a surface ionization ion source /57,36/. This combination is highly selective for Cs. The total efficiency is of the order of 80 - 90 %. The Cs-yield courve is shown in fig 10 /44/. The yield as well as the activity of the corresponding products are as follows:

Cs-isotope	yield atoms/,uA	product	yield Bq/s	mCi/h
123-Cs	5.0 * 10^{10}	123-I	7.3 * 10^8	71
125-Cs	1.1 * 10^{11}	125-I	1.4 * 10^4	1.5
127-Cs	1.3 * 10^{11}	127-Xe	2.9 * 10^4	2.8

Note that these activities are obtained for 1 ,uA proton beam intensity only. The molten La-target of the given design could withstand a beam current of 50 ,uA /50/. From this figures one can easy estimate: the system is able to produce multi-Ci quantities of 123-I and almost Ci-quantities of 125-I and 127-Xe simultaneously within a few hours. The isotopic impurities are determined from the mass-resolution of the isotope separator. The 125-I contamination in the final 123-I preparation will be of the order of 10^{-3} %.

^{167}Tm

The isotope 167-Tm is suitable for scintigraphic in vivo studies /59/. The best way to produce 167-Tm is via spallation reaction /58,59/. The most elegant way would be the application of ISOL-technique. As allready mentioned a Ta-powder target give highly selective Yb-isotopes /60/, the other rare earth elements are discriminated by surface effects. A Ta-foil target connected to the same ion-source produces isobars of the rare earth elements /33/ (fig.11). The production rate for 167-Yb is 1.1 * 10^{1} atoms/s and µA proton beam intensity. This gives an practical production yield for 167-Tm of approximately 1 mCi/µAh. The Ta-foil target of the given design could be irradiated with 100 µA proton beam current /50/.

^{211}At

In similarity to 123-I the medical important 211-At (radionuclide therapy) can be produced with satisfactorily isotopic purity via the 211-Rn /62/. The cross-sections for the formation of 211-Rn as well as for 211-At from uranium are significant smaller than for thorium as target /65/ (tab.1). ISOL-technique can be used to produce 211-At via the mother-nuclide in a very elegant way. ThO_2 or ThC_2 targets /61/ are connected to a plasma discharge ion source with cold line /36/. Practical yield of nearly 10^{7} 211-Rn atoms per second and µA proton beam intensity have been obtained /61,36/.

Conclusions

i. Spallation reaction is a very suitable route for production of some medical radioisotopes. Because of the limited number of corresponding accelerators as well as because of the priority of experiments at such facilities a regular supply of shortlived isotopes like ^{81}-Rb or 123-I produced in this way seems to be unrealistical. For longlived isotopes however a few production runs per year will be sufficient to organize a regular supply.

ii. Stable impurities in the targetmaterial, isotopic impurities due to the lack of reaction selectivity, waste problems and others are the main complicating factors in radiochemical processing of large spallation targets. ISOL-techniques open new ways in spallation radioisotope production and application. Isotope separation technique itself is also useful to be applied in "classical" RI-production to improve the isotopical purity.

iii. Modern physico-chemical data are of same relevance as nuclear data in radioisotope production. By knowing data for release, surface adsorption and ionization ISOL-technique is a suitable tool to determine simultaneously cross-sections.

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Tab.1 Review of spallation rection cross-section data for the radioisotopes discussed in this paper. The proton energy was limited to the 500 MeV region.

RADIO-NUCLIDE	TARGET	E_p (MeV)	CROSS-SECTION (10^{-30} m^2 = mb)	REF.
82-Sr	Zr	590	19 ± 4	53
	Nb	590	22 ± 4	53
	Mo	590	15 ± 3	53
	Mo	800	24.5 ± 0.8	56
	Mo	800	23 ± 1	46
	RbBr	800	2.1 ± 0.2	54
85-Sr	Mo	800	48 ± 0.7	46
	Mo	800	50 ± 2	56
123-Xe	La/Cu	590	36 ± 5	53
	La/Cu	590	45 ± 6	54
	I	660	3.8 ± 0.4	18
	Cs	660	29.3 ± 1.7	18
	Ba	660	26 ± 4	18
	La	660	31.9 ± 1.6	18
125-Xe	La/Cu	590	57 ± 9	53
	La/Cu	590	43 ± 9	54
	I	660	6.6 ± 0.5	18
	Cs	660	45 ± 0.5	18
	Ba	660	38 ± 6	18
	La	660	47.7 ± 3.9	18
127-Xe	La/Cu	590	53 ± 11	53
	La/Cu	800	51 ± 7	56
123-I	La/Cu	590	57 ± 6	54
	La/Cu	590	57 ± 9	53
	La	800	51 ± 3	56
167-Tm	Lu	590	56 ± 6	58
	Hf	590	51 ± 10	58
	Ta	590	49 ± 7	58
	W	590	49 ± 7	58
168-Tm	Lu	590	5 ± 1	58
	Hf	590	6 ± 2	58
	Ta	590	0.8 ± 0.4	58
	W	590	0.4 ± 0.2	58
211-Rn	Th	660	13 ± 6	63
211-At	Th	660	18.2 ± 2.2	64
	U	660	5.2 ± 1.4	64

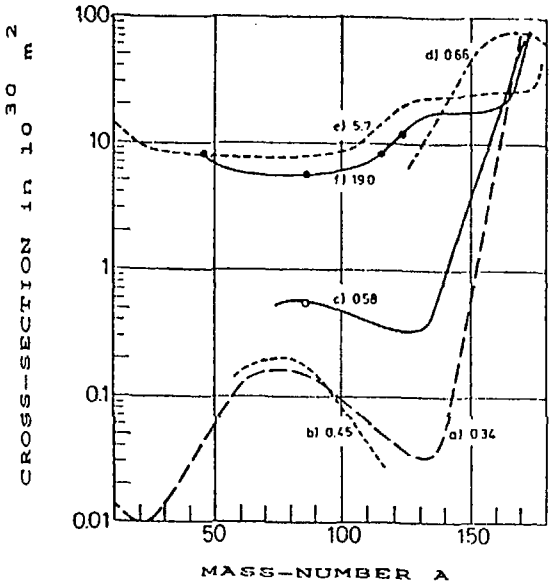


Fig. 1 Mass distribution for reaction products formed in interaction of Ta with protons of different energies (taken from /16/)

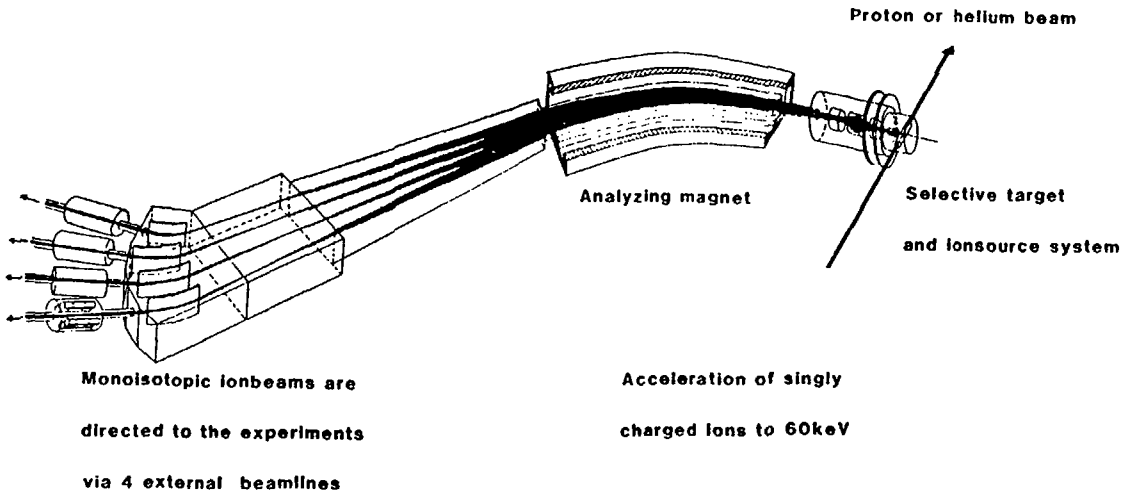


Fig. 2 The principle of on-line mass separation

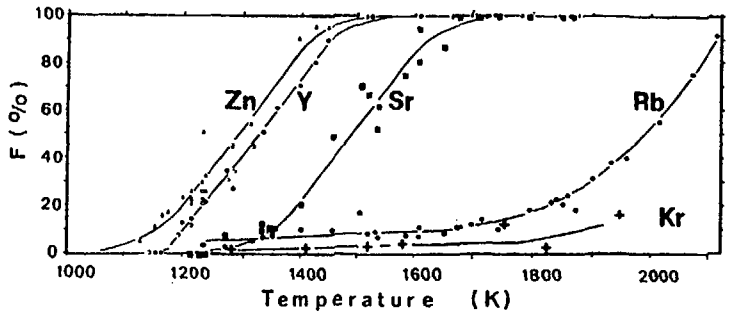


Fig. 3 Release of some spallation reaction products from 0.1 mm thick Zr-foils irradiated with 660 MeV protons (release time 10 minutes) /26/

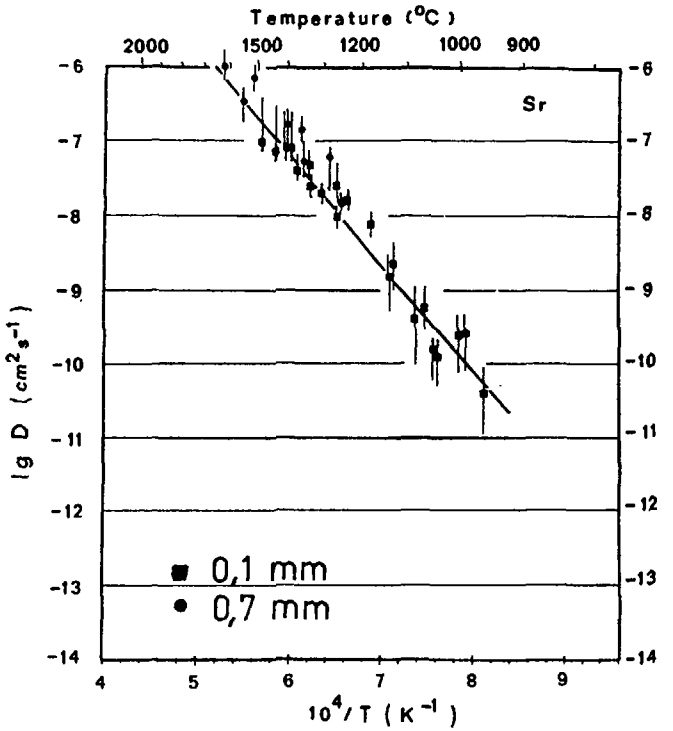


Fig. 4 ARRENIUS-plot for the diffusion of Sr in polycristalline Zr /26/

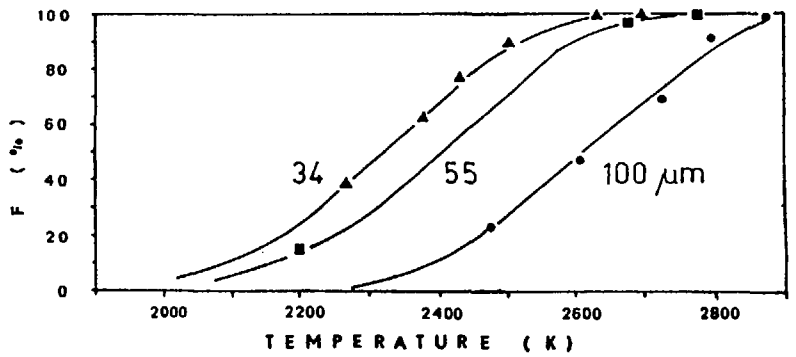


Fig. 5 Release of Y from Mo-foils of different thickness irradiated with 660 MeV protons (annealing time 5 minutes) /29/

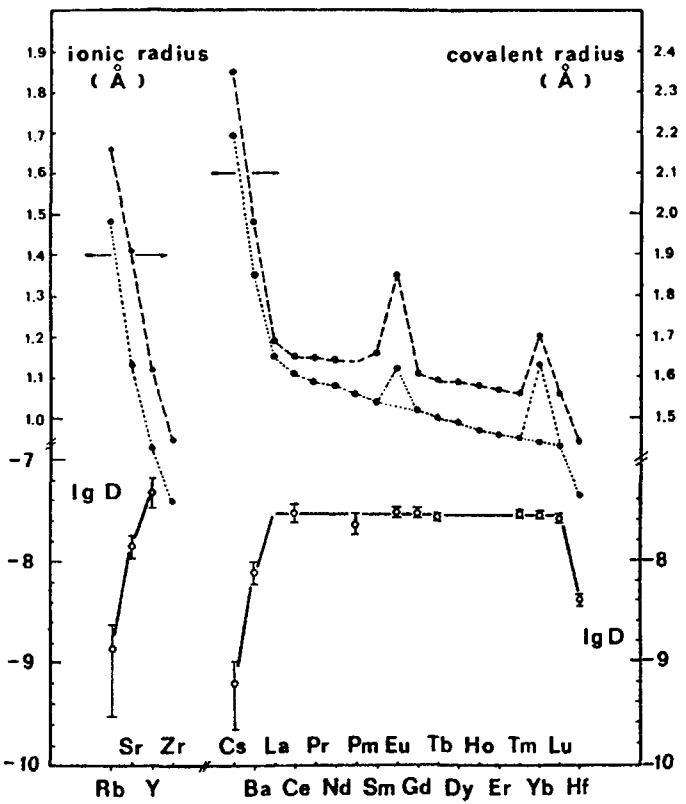


Fig. 6 Diffusion coefficients of spallation reaction products in polycristalline Ta (lower part) in comparison with the atomic and ionic radii of the diffusing particles (upper part). Ta-foils of 83 µm thickness were irradiated with 660 MeV protons. The diffusion coefficients were determined for the indicated elements simultaneously from release studies, the annealing temperature was 2750 K, annealing time 300 s. No significant differences in the diffusion behaviour of the rare earth elements has been observed, they all diffuse faster then Sr and Ba.

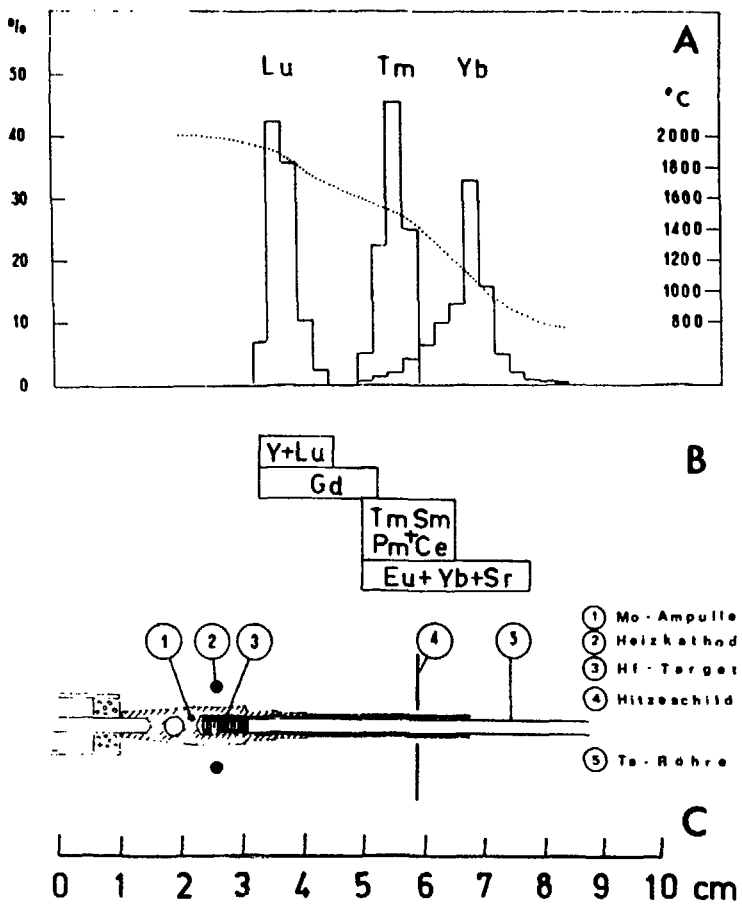


Fig. 7

Thermochromatographical separation of carrier free rare earth radioisotopes in vacuum. The rare earth radio nuclides are formed in spallation reaction by irradiating a Hf-target (3) with 660 MeV protons. The Hf-target was inserted into a Mo-crucible (1) equiped with a thermochromatographic Ta-tube (5). The crucible containing the target was heated to 2170 K by electron bombardment (2). All rare earth radioisotopes are released and adsorped according theire adsorption energies along the Ta-tube. Everage annealing time was 10 Minutes /30,34/.

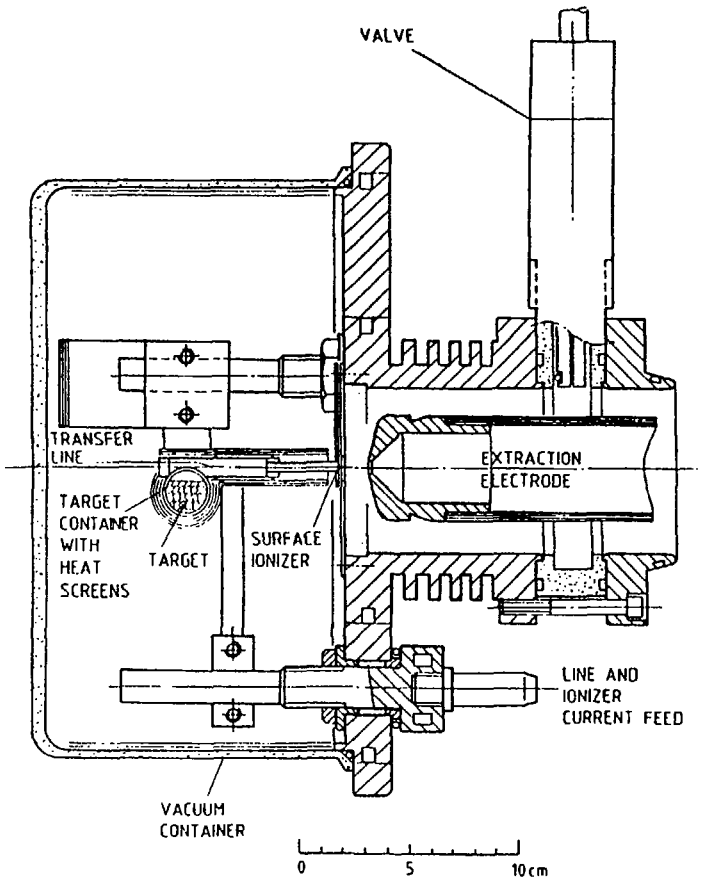
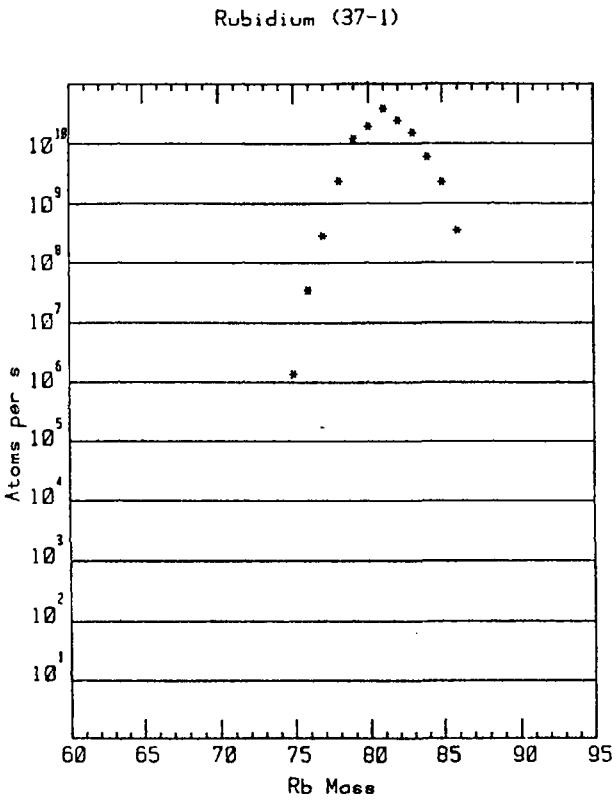
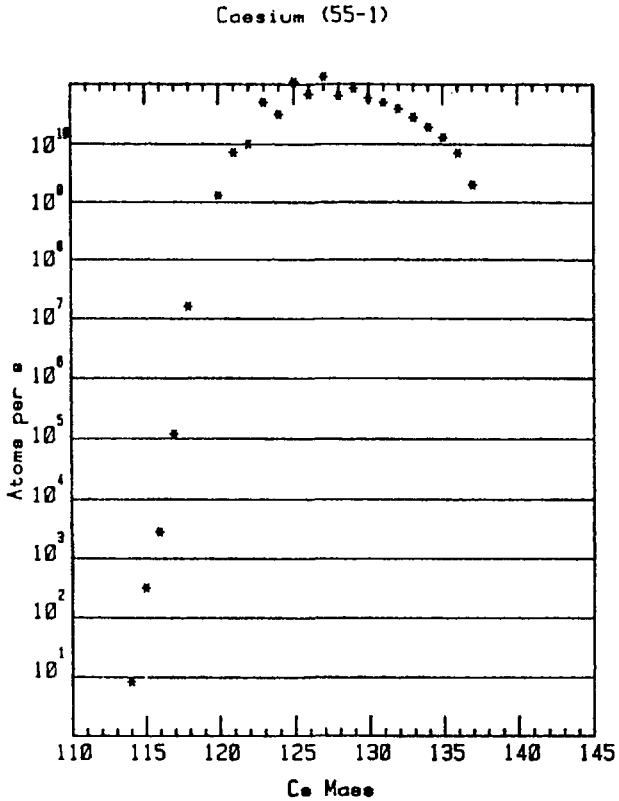


Fig. 8 Scheme of target ion source system for the case of a surface ionization ion source. In addition the extraction electrode is shown fixed to the acceleration chamber. (taken from /44/)



Date : 14.6.85
Target material : Niobium powder
Ion source : Ta-surface ionization
Target thickness: 50 g/cm^2
Projectile : 600 MeV protons

Fig. 9 Yield curve for the production of Rb-isotopes at ISOLDE from a 50 g/cm^2 Nb-powder target taken from /44/.



Date : 16.10.78
Target material : Molten lanthanum
Ion source : Ta-surface ionization
Target thickness: 140 g/cm^2
Projectile : 600 MeV protons

Fig. 10 Yield curve for the production of Cs-isotopes from a 140 g/cm^2 molten La target and a 1 µA 660 MeV proton beam in 1 second (taken from /44/).

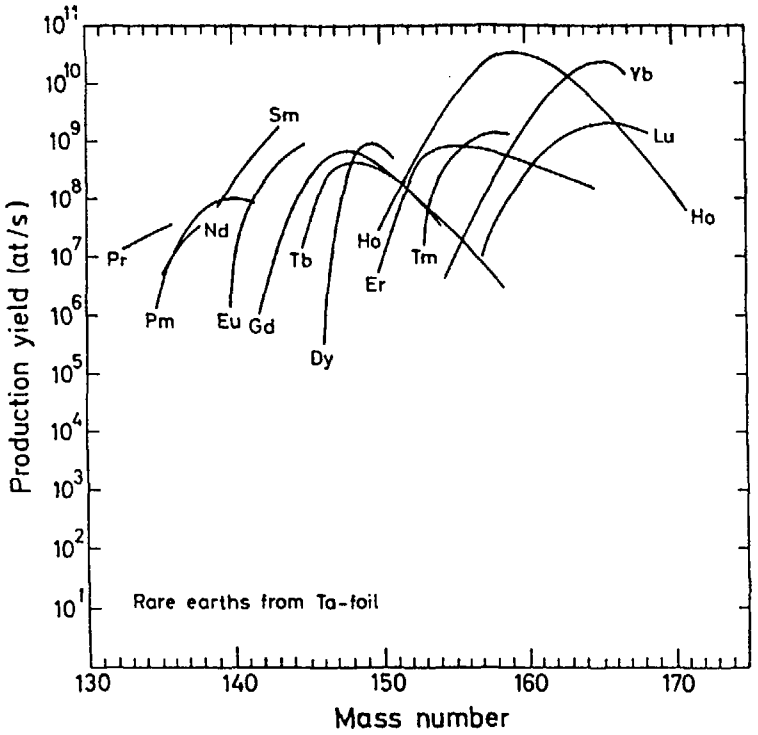


Fig. 11 Production yields of lanthanoid isotopes from a 122 g/cm² Ta-foil target connected to a positive surface ionizer. Individual measurement points are not indicated. (taken from /33/)

PHOTONUCLEAR REACTIONS FOR RADIOISOTOPE PRODUCTION

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› Abstract ‹

Because of the lack of reliable yield data in the energy region below 70-MeV, the yields of several photonuclear reactions were calculated and compared to the data obtained above 200-MeV region. Then, in this experiment, the calculated yield per equivalent quanta for $^{63}Cu(\gamma,n)^{62}Cu$ reaction was used as the monitor yield. And the relative yield ratio of the $^{65}Cu(\gamma,n)^{64}Cu$ to the $^{63}Cu(\gamma,n)^{62}Cu$ was obtained experimentally as 1.3 and also used for comparison.

Again, in order to elucidate the general features of photonuclear reaction, the activation yield curves were presented for a number of photonuclear reactions in the energy range from 30 to 68-MeV and the yield maps of (γ,n), (γ,p) and (γ,pn) reactions were showed as functions of both target mass number and bremsstrahlung maximum energy. These figures may be useful in case of the estimation of radioisotope production.

‹ Introduction ›

In spite of the usefulness of radioisotopes produced through photonuclear reactions, the yield data of photonuclear reactions are very few, especially in the energy region below 70-MeV, which is useful for isotope production. In this work, the various photonuclear reaction yields have been measured at 30 to 68-MeV. Then, the yield maps were presented in order to show the general feature of photonuclear reaction.

‹ Photonuclear reaction ›

The excitation function of photonuclear reaction has a large peak in the photon energies ranging from 25-MeV for low Z to 14-MeV for high Z element. This is called the "giant resonance". When a nucleous is excited by photons at these resonance energy, one or two neutrons or charged particles may be knocked out from target nucleous. The (γ,n) reaction gives the highest yield among various types of photonuclear reactions. The deficiency of neutrons in the produced nuclide leads to positron emission for light elements and/or electron capture for medium and heavy elements. The above reaction products are obtained usually in non carrier-free state. When carrier-free radioisotopes are required, the (γ,p),(γ,α) and (γ,pn) reactions should be utilyzed effectively. But the yields of these reactions are lower than that of (γ,n) reaction in cases of medium and heavy elements.

‹ Yield calculation ›

Recently, M. Van Der Leij et al[1] have tried to compare a number of data of F-18 production yield obtained on solid targets, and pointed out that the yields were given in a wide range as shown in Table 1.

In general, photonuclear reaction yields depend on the various experimental factors, such as, beam profile, resolution of accelerated electron, atomic number of bremsstrahlung converter and its thickness, size of target and distance between the converter and target. Accordingly, it is very hard to get useful yield data which are independent on such experimental conditions. In order to obtain useful yield data of various photonuclear reactions, it is important to determine the most reliable monitor reaction, because it is very difficult to know the incident flux of bremsstrahlung directly.

By using the equivalent quanta, Q, which are usually used in the high energy region above 100-MeV, the yield per equivalent quanta for the given reaction, σ_Q, is given by

$$\sigma_Q = Q^{-1} \int_{E_{th}}^{E_{max}} \sigma(k)\phi(k,E_{max})k^{-1}dk, \qquad (2)$$

where E_{th}, E_{max}, $\sigma(k)$, and $\Phi(k,E_{max})$ are the threshold energy for the reaction, the bremsstrahlung maximum energy, the excitation function in cm^2 per nucleus, and the number of photons at a energy k per cm^2 per sec, respectively. The equivalent quanta, Q, are defined as follows,

$$Q = E_{max}^{-1} \int_{0}^{E_{max}} \phi(k,E_{max})dk. \qquad (3)$$

The integral part of equation (3) is the power of bremsstrahlung.

Then, the saturated radioactivity, R, is given by

$$R = N \int_{E_{th}}^{E_{max}} \sigma(k)\phi(k,E_{max})k^{-1}dk. \qquad (4)$$

The number of atoms, N, is calculated by $(W/A)\cdot\theta\cdot N_0$, where W, A, θ and N_0 are weight of element, a atomic weight, an isotopic abundance, and the Avogadro's number, respectively. When Eq.(2) is substituted in Eq.(4), the following simple relation is resulted,

$$R = N\cdot\sigma_Q\cdot Q \qquad (5)$$

If Q is measured using two monitor foils placed in front and behind the target and if the induced radioactivity is divided by saturation factor, the yield per equivalent quanta can be calculated easily.

‹ Monitor reaction ›

Unfortunately, measurements of absolute yields per equivalent quanta have not yet been done at the electron energy below 100-MeV. Hence, the numerical integration was carried out by using the tables of the thick target bremsstrahlung spectrum reported by Penfold and Leiss[2], to be proportional to the integrated angular cross section as given by Sciff[3], and by using the excitation functions for the $^{65}Cu(\gamma,n)^{64}Cu$ and the $^{63}Cu(\gamma,n)^{62}Cu$ reactions reported by Katz and Cameron[4], and that for the $^{12}C(\gamma,n)^{11}C$ reaction repoted by Barber et al.[5] As example, the calculated yields of the $^{63}Cu(\gamma,n)^{62}Cu$ reaction are shown in Table 2, along with the data expressed by using the unit of yield per mole per roentgen. In Fig. 1, the calculated yields of the above monitor reactions are plotted against the bremsstrahlung maximum energies. Each curves in the yield per mole per roentgen shows maximum in the vicinity of 20 to 30-MeV, and then decreases gradually with increasing energy. Such a behavior might be derived from the decreasing in the photon flux required to produce 1 R as a function of photon energy[6]. Therefore the unit of yield per mole per roentgen cannot express the photon flux exactly. The yields per equivalent quanta for the $^{63}Cu(\gamma,n)^{62}Cu$ and the $^{12}C(\gamma,n)^{11}C$ reactions can be well extended to the yield curves determined by Masaike[7] in the energies above 200-MeV. Comparing other various data, it is concluded that the activation yield curve for the $^{63}Cu(\gamma,n)^{62}Cu$ reaction in Fig. 1 can be used as the useful monitor yield curve. Moreover, the average value of 1.3 for the relative yield ratio of the $^{65}Cu(\gamma,n)^{64}Cu$ to the $^{63}Cu(\gamma,n)^{62}Cu$ was obtained experimentally in the energy range from 30 to 70-MeV, and this value is also used for comparison.

‹ Experimental ›

Bremsstrahlung irradiations were conducted with the 300-MeV linear electron accelerator of Tohoku University. The linac was operated with the high-current accelerating section. The maximum intensity was attained at 50 to 60-MeV in this section. The energy resolution was ±3% and beam size was about 3-mmϕ. The

pulse repetition rate was 300-pps with pulse width of 3-μs. Irradiation assembly used[8] is shown in Fig. 2. The bremsstrahlung was generated with a platinum converter of 2-mm thick. The average beam current was about 100 or 150 μA in this work. The equivalent quanta can be estimated by multiplying the conversion factor and geometrical factor. Scince the Pt converter of 2-mm corresponds to 0.7 radiation length, 50% of electrons are converted to bremsstrahlung.

In the typical irradiation conditions, the fluxes of bremsstrahlung were calculated to be 2.0 X 10^{13}/cm^2/sec (7.0 X 10^6 R/min) and 1.0 X 10^{14}/cm^2/sec (5.2 X 10^7 R/min) at 30 and 60-MeV, respectively. In this experiment, the geometrical factor was estimated as follows. When 50 % of 60-MeV electrons having average beam current of 120-μA (The beam power is 7.2-KW) is converted to bremsstrahlung, the equivalent quanta are given as

$$7200 \times 0.5 \text{ J/s} / (60 \times 10^6 \times 1.602 \times 10^{-19} \text{ J}) = 3.7 \times 10^{14}.$$

Since the measured quanta on the target were resulted in the order of about 10^{14}, the geometrical factor was also estimated to be a quarter.

‹ Activation yield curves ›

The activation yield curves obtained in the energy range of 30 to 68-MeV in this work are shown in Fig 3-8. In these cases, a particular radioisotope may be induced through a different isotope in the same element. However, the main reaction was decided by considering the natural isotopic abundance, mass-threshold, coulomb barrier and other nuclear effect.

On the other hand, in order to elucidate the general feature of the yield values, the yield maps obtained for the (γ,n), (γ,p) and (γ,pn) reactions are shown in Fig. 9, 10 and 11. In these figures, the yield levels were drawn as function of bremsstrahlung maximum energy and target mass number. The yield "zero" means the calculated threshold energy. The yield values at 20-MeV were calculated on the basis of the data reported by Oka et al.[9]

From Fig. 9, it is obvious that the (γ,n) reactions take place in the 10-MeV, and their yield values increase markedly with increasing energies up to 30-MeV. Then the yields are dependent on the mass number rather than on E_{max} , especially at above 30-MeV. This tendency is remarkable for the reactions on the targets with the mass number up to 50. The yields of (γ,xn) reactions also shows similar pattern, though their energy dependence are markedly at above 30-MeV. On the contrary, the (γ,p) and (γ,pn) reactions show quite different patterns. The yield curves of the former show minima at target mass numbers around 50. In this mass region, the yields are increased with a given bremsstrahlung maximum energy, and then decrease with increasing mass number because of the potential barrier restrictions. The yield curves of the (γ,pn) reactions also exhibit similar patterns to those of the (γ,p) reactions, though the former has higher thresholds and lower yield values than the latter. In addition, it will be expected that the yield curves

of (γ,α) and $(\gamma,\alpha n)$ reactions also show similar pattern as aboves, though their yields are lower than those of the aboves.

From above figures, the excitation energy in the case of the isotope productions by the (γ,n) reactions is enough at 30-MeV. But in the cases of (γ,p) or (γ,pn) reactions, the excitation energy of 50 or 60 MeV would selected.

‹ Examples of isotope production ›

By using Eq. (5), the production rate of an arbitrary radioisotope can be calculated easily. Two examples are shown as follows.

(1) F-18 production

It is assumed that one gram of fluorine is irradiated in close contact with back of the converter at energy of 30 or 60-MeV. The number of nuclide, N is $6.02 \times 10^{23}/19$. The yield is 2- mb at 30-MeV or 2.5 mb at 60-MeV[10]. The equivalent quanta are 6×10^{13} at 30-MeV or 1×10^{14} at 60-MeV, respectively. Multiplying these values, the saturated F-18 activities are resulted in 3.8 GBq or 7.9 GBq, respectively. These values are agreed with the results obtained experimentally by M. Yagi and R. Amano[11], as shown in the data of Ref.8 in Table 1.

(2) Carrier-free Cu-67 production

It is also assumed that one gram of Zinc is irradiated for 10-hrs in a similar manner as above at energy of 60-MeV, using the $^{68}Zn(\gamma,p)^{67}Cu$ reaction. The yield is estimated to be about 6 mb on the basis of the data obtained by Kato et al.[12] The saturation factor of 10-hrs irradiation is 0.106, while the abundance of target nuclide, ^{68}Zn, is 18.8 %. By calculating a similar manner as above, the 0.11 GBq is obtained.

Reference

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Table 1. Saturation yields on solid targets for the $^{19}F(\gamma, n)^{18}F$ reaction per gram of ^{19}F for a beam of 100 μA electrons

E_0 (MeV)	Yield (GBq)	Converter	Distance target–converter	Ref.
20	1.5	2 mm Pt	close	2
20	0.16	W	7.5 cm	1
25	0.43	W	7.5 cm	1
25	0.11		close	6
30	3.4	3 mm Pt	close	8
40	1.3	6 mm Pt	0.5 cm	4
40	0.56			7
60	5.9	3 mm Pt	close	8
77	0.4	0.5 mm W	57 cm ($f = 0.066$)*	this work
125	1.1	0.5 mm W	57 cm ($f = 0.147$)*	this work

* Here f is the fraction of the total number of produced photons that hit the target.[10]

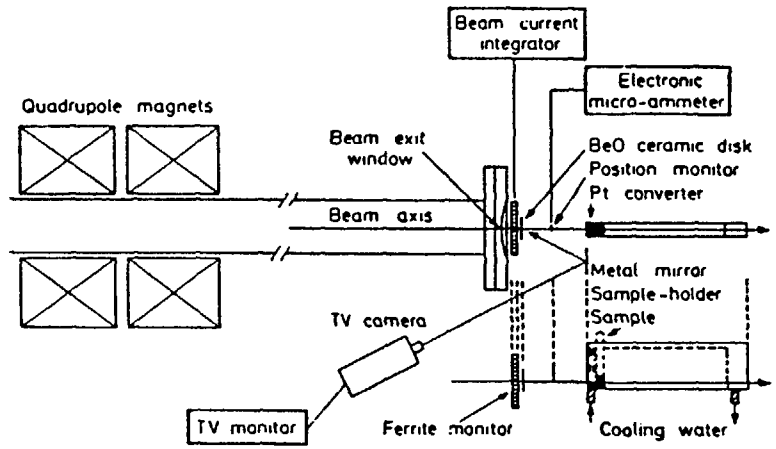

Fig. 1. Schematic drawing of the irradiation system

Table 2. The calculated yields of $^{63}Cu(\gamma,n)^{62}Cu$ reaction expressed by per mole per roenten and per equivalent quanta.

E_{max}	Calculated yield /mole/R	/eq. quanta
20 MeV	2.2×10^{6}	23×10^{-27}
30	2.6×10^{6}	36×10^{-27}
40	2.3×10^{6}	39×10^{-27}
50	2.0×10^{6}	41×10^{-27}
60	1.8×10^{6}	43×10^{-27}
70	1.6×10^{6}	44×10^{-27}

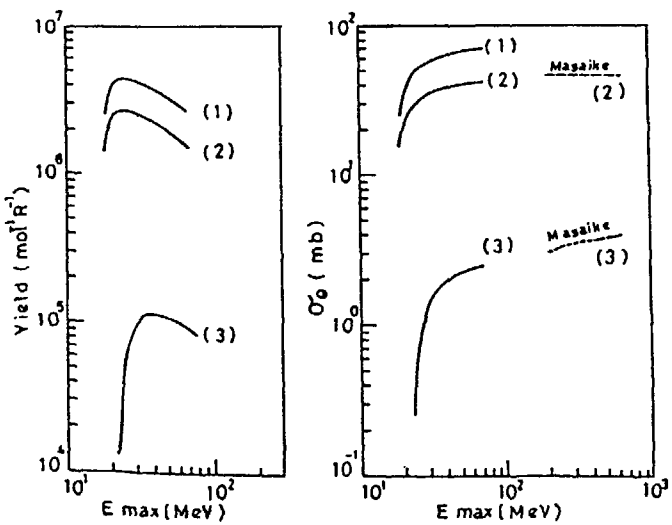

Fig. 2. Activation yield curves for the monitor reactions. (1) $^{65}Cu(\gamma, n)^{64}Cu$; (2) $^{63}Cu(\gamma, n)^{62}Cu$; (3) $^{12}C(\gamma, n)^{11}C$.

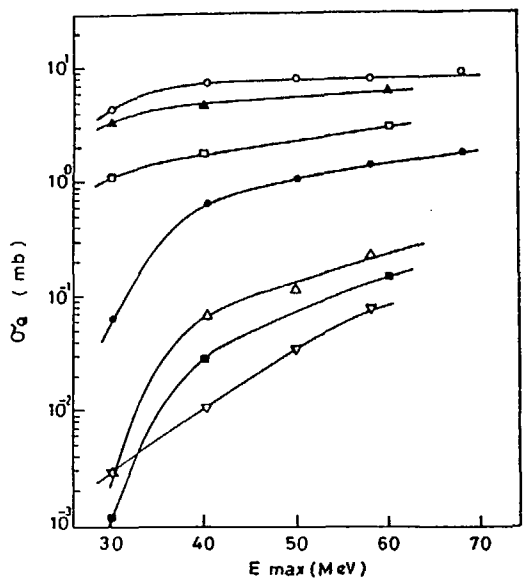

Fig. 3. Activation yield curves for the reactions on C, Na, Mg and Al.
□ $^{12}C(\gamma, n)^{11}C$, ■ $^{12}C(\gamma, \alpha n)^{7}Be$, ▲ $^{23}Na(\gamma, n)^{22}Na$,
○ $^{25}Mg(\gamma, p)^{24}Na$, ● $^{24}Mg(\gamma, pn)^{22}Na$, △ $^{27}Al(\gamma, \alpha n)^{22}Na$,
▽ $^{27}Al \rightarrow {}^{24}Na$.

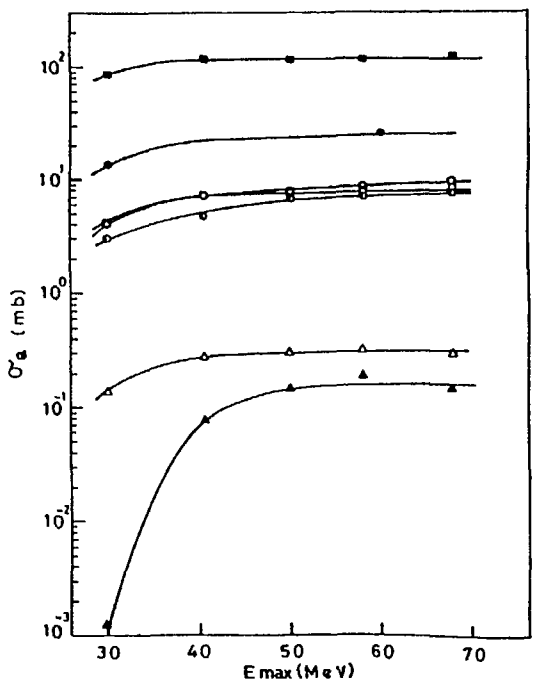

Fig. 4. Activation yield curves for the reactions on Ca, Ti ar V.
■ $^{48}Ca(\gamma, n)^{47}Ca$, □ $^{44}Ca(\gamma, p)^{43}K$, ● $^{46}Ti(\gamma, n)^{45}Ti$,
○ $^{48}Ti(\gamma, p)^{47}Sc$, ◐ $^{49}Ti(\gamma, p)^{48}Sc$, △ $^{51}V(\gamma, \alpha)^{47}Sc$,
▲ $^{51}V(\gamma, \alpha n)^{46}Sc$.

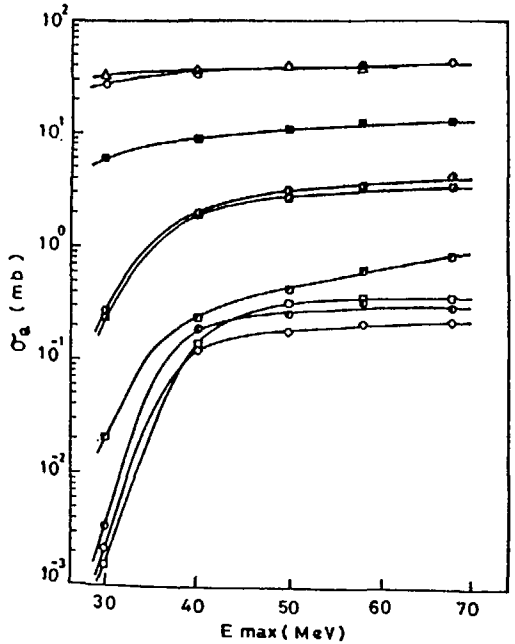

Fig. 5. Activation yield curves for the reactions on Cr, Mn and Fe.
○ $^{52}Cr(\gamma, n)^{51}Cr$, ◑ $^{50}Cr(\gamma, pn)^{48}V$, ◐ $^{50}Cr(\gamma, 2n)^{48}Cr$,
△ $^{55}Mn(\gamma, n)^{54}Mn$, ■ $^{57}Fe(\gamma, p)^{56}Mn$, ▨ $^{54}Fe(\gamma, pn)^{52g}Mn$,
▨ $^{56}Fe(\gamma, pn)^{54}Mn$, □ $^{56}Fe(\gamma, \alpha n)^{51}Cr$, ◇ $^{54}Fe(\gamma, 2n)^{52}Fe$.

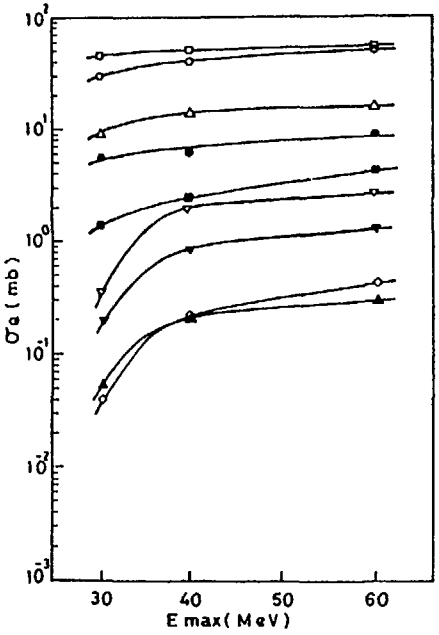

Fig. 6. Activation yield curves for the reactions on Co, Ni and Cu.
○ $^{59}Co(\gamma, n)^{58}Co$, ● $^{59}Co(\gamma, 2n)^{57}Co$, △ $^{58}Ni(\gamma, n)^{57}Ni$,
▽ $^{58}Ni(\gamma, pn)^{56}Co$, ▼ $^{60}Ni(\gamma, pn)^{58}Co$, ▲ $^{58}Ni(\gamma, 2n)^{56}Ni$,
□ $^{65}Cu(\gamma, n)^{64}Cu$, ■ $^{63}Cu(\gamma, 2n)^{61}Cu$, ◇ $^{63}Cu(\gamma, \alpha n)^{58}Co$.

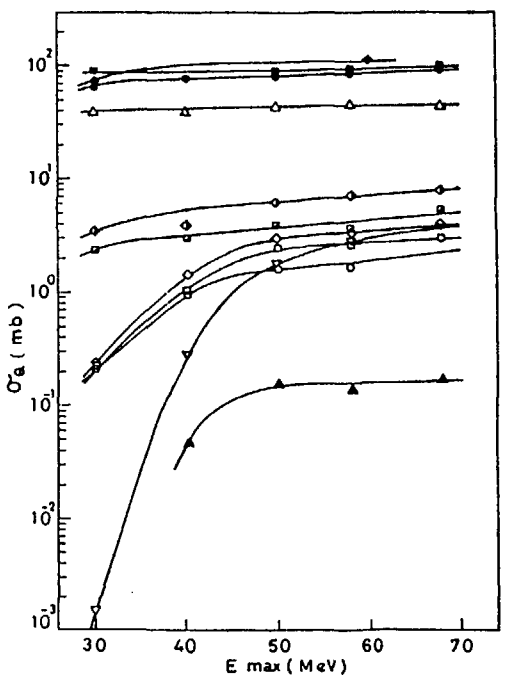

Fig. 7. Activation yield curves for the reactions on Y, Zr, Nb and Mo.
◆ $^{89}Y(\gamma, n)^{88}Y$, ● $^{90}Zr(\gamma, n)^{89}Zr$, ○ $^{90}Zr(\gamma, pn)^{88}Y$,
△ $^{93}Nb(\gamma, n)^{92m}Nb$, ▲ $^{93}Nb(\gamma, \alpha n)^{88}Y$, ■ $^{100}Mo(\gamma, n)^{99}Mo$,
◈ $^{97}Mo(\gamma, p)^{96}Nb$, ◪ $^{96}Mo(\gamma, p)^{95m}Nb$, ◇ $^{94}Mo(\gamma, pn)^{92m}Nb$,
□ $^{92}Mo(\gamma, 2n)^{90}Mo$, ▽ $^{94}Mo(\gamma, \alpha n)^{89}Zr$.

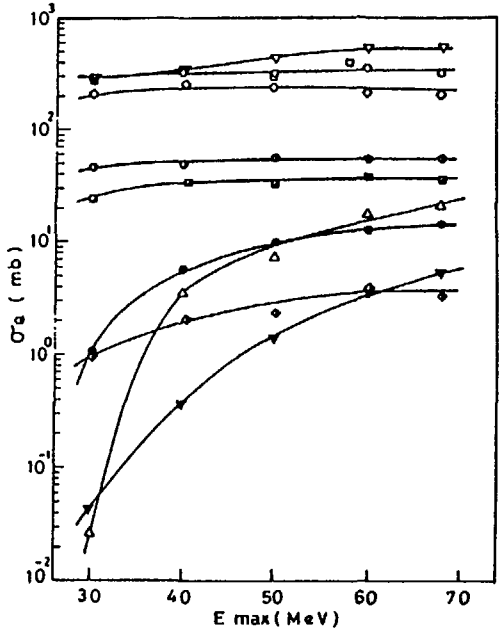

Fig. 8. Activation yield curves for the reactions on Pb, Tl and Hg.
□ $^{204}Hg(\gamma, n)^{203}Hg$, ◇ $^{198}Hg(\gamma, n)^{197g}Hg$,
◪ $^{198}Hg(\gamma, n)^{197m1}Hg$, ◈ $^{199}Hg(\gamma, p)^{198}Au$,
▽ $^{204}Pb(\gamma, n)^{203}Pb$, ▼ $^{204}Pb(\gamma, 2n)^{202m}Pb$,
△ $^{204}Pb(\gamma, 3n)^{201}Pb$, ○ $^{203}Tl(\gamma, n)^{202}Tl$,
◑ $^{203}Tl(\gamma, 2n)^{201}Tl$, ● $^{203}Tl(\gamma, 3n)^{200}Tl$.

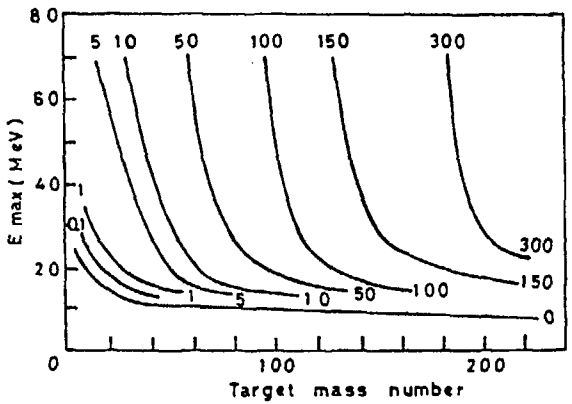

Fig. 9. Yields of the (γ, n) reactions as a function of bremsstrahlung maximum energy and target mass number. The numerical values in the figure are yields per equivalent quanta in mb.

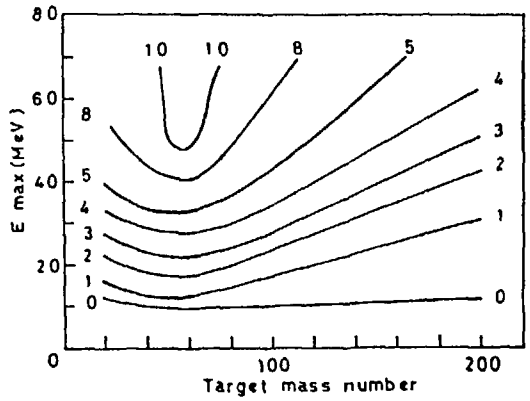

Fig. 10. Yields of the (γ, p) reactions as a function of bremsstrahlung maximum energy and target mass number. The numerical values in the figure are yields per equivalent quanta in mb.

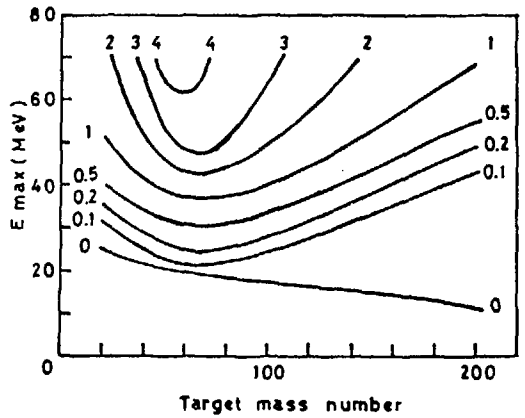

Fig. 11. Yields of the (γ, pn) reactions as a function of bremsstrahlung maximum energy and target mass number. The numerical values in the figure are yields per equivalent quanta in mb.

THE CONTRIBUTION TO NUCLEAR DATA FOR BIOMEDICAL RADIOISOTOPE PRODUCTION FROM THE MILAN CYCLOTRON LABORATORY

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Abstract

At the Cyclotron Laboratory of the Milan University, the cyclotron production of biomedical radioisotopes has been carried out for research purposes since the early seventies. In this period, experimental thin-target excitation functions for proton induced nuclear reactions have been measured with the single target activation technique, in the energy range from 5 to 45 MeV. Other than the "conventional" nuclear reactions such as $^{124}Te(p,xn)$, $^{nat}Tl(p,xn)$, $^{203}Tl(p,xn)$, $^{nat}Kr(p,xn)$ and $^{nat}Ga(p,xn)$, some unusual, and sometimes unpublished data, are presented, for reactions relevant from the point of view of medical applications. Amongst them: $^{nat}Hg(p,xn)$, $^{202}Hg(p,xn)$, $^{nat}Mo(p,xn)$, $Au(p,3n)^{195m,195}Hg/^{195m}Au$, $^{nat}Ag(p,xn)^{107,109}Cd/^{107m,109m}Ag$, $^{nat}Pb(p,xn)$, $^{nat}Ta(p,xn)^{178}W/^{178m}W$, $^{nat}Sb(p,xn)^{123m}Te,^{118}Te/^{118}Sb$, etc. In recent years (1983 and 1985) two other cyclotrons have been installed in Italy. A brief status report about the italian situation in this field is presented.

1. INTRODUCTION

The "thin-target excitation functions, t.t.e.f." (i.e: the behaviour of "thin-target" yield, t.t.y., of a radionuclide vs charged particle energy) are fundamental data for the computation of both yield and radionuclidic purity of accelerator produced radioisotopes.

In case of either monoisotopic or highly enriched target made of a pure element, the t.t.y. is easily related to the cross section $\sigma(E)$ of a particular reaction channel, through the equation:

$$(1)\quad \text{t.t.y. } [\text{Bq C}^{-1}\ \text{MeV}^{-1}] \equiv y(E) = \frac{\lambda\ (S\ \rho)\ (N_a/M)\ \sigma(E)}{Q\ \left[(dE/dx)_E\ \Delta x\right]}$$

in which:

λ ≡ decay constant $[s^{-1}]$

$S\ \rho = \Delta x$ ≡ target thickness $[g\ cm^{-2}]$

S ≡ geometrical target thickness [cm]

ρ ≡ target density $[g\ cm^{-3}]$

N_a ≡ Avogadro number [atoms gatom^{-1}]

M ≡ target atomic mass $[g\ gatom^{-1}]$

$\sigma(E)$ ≡ reaction cross-section $[cm^2]$ at energy E [MeV], where: 1 $[cm^2]$ ≡ 10^{24} [barn]

Q ≡ total integrated charge [C]

$(dE/dx)_E\ \Delta x = \Delta E$ ≡ "thin-target" energy loss [MeV] at energy E [MeV]

$(dE/dx)_E = S(E)$ ≡ target stopping power [MeV g^{-1} cm^2] at energy $E = (E^{in} + E^{out})/2$, where:

E^{in} = mean energy of the particles incoming on the target, E^{out} = mean energy of the particles outcoming from the target. Infact, even in case of "thin-target"♯, the particle energy E is assumed to be the "mean" value of the energy in the target itself, as a consequence of the fact that any particle beam of mean energy E is characterized by an "energy spread" σ_E, so that: $E^* = E \pm \sigma_E$.

♯ A common definition of "thin-target" is: "A target in which the energy loss is negligible in respect to the beam energy (i.e: $\Delta E/E \sim 0.01$–0.05)".

In case of non-pure target elements (alloys, stoichiometric or non-stoichiometric compounds, mixtures of known composition, etc.), the Bragg-Kleeman approximation, eq.(2), for energy loss calculations is generally accepted [1,2].

Thus, for compounds and mixtures of k elements, the total stopping power is:

$$(2) \qquad S_T(E) = \Sigma_i\, w_i\, S_i(E) \qquad [\text{MeV g}^{-1}\ \text{cm}^2]$$

where: $S_i(E)$ ≡ stopping power of i-th target element

w_i ≡ weight fraction of i-th target element,

with: $\Sigma_i\, w_i = 1$, (i = 1,2,..,k)

and the total range at the energy E is computed as:

$$(3) \qquad R_T(E) = \int_{E^\circ}^{E} \frac{dE}{S_T(E)} \qquad [\text{g cm}^{-2}]$$

Computer programs are commonly used for the calculation of both $S_T(E)$ and $R_T(E)$.

The previous definition, eq.(1), is easily extended to multiisotopic target elements:

$$(4) \qquad \text{t.t.y.} \equiv y(E) = \frac{\lambda\, N}{Q\ \Delta E} \sum_i^n p_i\, \sigma_i(E)$$

in which:

p_i ≡ isotopic fraction , with: $\Sigma_i\, p_i = 1$

$\sigma_i(E)$ ≡ cross section of reaction [cm^2] induced on i-th target isotope at energy E , (i = 1,2,...,n)

$N = (S\ \rho)\ (N_a/M)$ [atoms cm^{-2}]

$M = \Sigma_i\, p_i\, M_i$ ≡ target atomic mass [g $gatom^{-1}$]

M_i ≡ atomic mass of i-th target isotope [g $gatom^{-1}$]

$\Sigma_i\, p_i\, \sigma_i(E) = \bar{\sigma}(E)$ ≡ "effective" production cross-section of a well defined radioisotope##

In the common definition, the term "cross-section" is referred to a well defined "target nuclide", i.e: $\sigma_i(E)$. Moreover, the term "total cross-section" refers to the summation of the cross-sections of any reaction channel on a well defined target nuclide.

It is opinion of the author that, from nuclear chemistry and production point of view, the yield is a parameter with a more direct and practical significance in respect to cross-section, and therefore it is more commonly used. On the other hand, it is evident that the cross-section is the primary physical parameter which describes the nuclear process.

Nevertheless, this primary physical meaning vanishes whenever the term "production cross section" is used in case of multiisotopic target element.

1.1. Thin-Target Yield, t.t.y.

In conformity with the modern and common definition, the t.t.y. is computed at the End Of an "Instantaneous" Bombardment, EOIB, and has the analytical meaning of the slope (at the beginning of irradiation) of the growing curve of a radionuclide vs irradiation time τ, per unit particle energy loss:

$$(5) \qquad y^{EOIB}(E) = \left[\frac{d}{d\tau} \left(\frac{d(a/I)}{dE} \right) \right]_{\tau=0}$$

with modern SI units, the t.t.y. is given in Bq C^{-1} MeV^{-1} (or ... MBq C^{-1} MeV^{-1}, GBq C^{-1} MeV^{-1}). With the old, but very commonly used units, the t.t.y. is given in μCi μAh^{-1} MeV^{-1} (or ... mCi μAh^{-1} MeV^{-1}), where μAh is intended to be a charge "instantaneously" collected on the target (i.e: 1 [μAh] = 3600 [μC]) !###

It is opinion of the author that the fact that time appears in explicit way in the charge units (i.e: μAh or ... μAs), might cause the misunderstanding of the existance of a linear relationship between activity produced and irradiation time.

Under the previous assumptions, the following equality holds:

$$1\ [\mu\text{Ci}/\mu\text{Ah}] = 37.0/3.6\ [\text{MBq/C}]$$

a ≡ activity [Bq or ... MBq, GBq]

I ≡ beam intensity [A or ... μA]

τ ≡ irradiation time [s]

dE ≡ differential "thin-target" energy loss [MeV]

a/I = h ≡ activity produced per beam intensity unit [Bq A^{-1} or ... MBq μA^{-1}, GBq μA^{-1}].

In the simple case of 1st order decay, t.t.y. is calculated from the experimental data from the conventional equation[3]:

$$(6)\quad y^{EOIB}(E) = \frac{C_\gamma}{[\alpha_\gamma\ \varepsilon_\gamma\ \Delta]\ Q\ \Delta E}\left(\frac{\lambda\ \Delta}{1 - e^{-\lambda\Delta}}\right)\left(\frac{\lambda\ \tau}{1 - e^{-\lambda\tau}}\right) e^{\lambda t}$$

$$(6')\quad = \frac{C_\gamma}{[\alpha_\gamma\ \varepsilon_\gamma\ \Delta]\ Q\ \Delta E}\ D(\Delta)\ \ G(\tau)\ \ e^{\lambda t}$$

in which:

C_γ ≡ net photopeak area [counts] of γ-emission of energy E_γ, at time t

t ≡ waiting time from EOB to the beginning of the measurement [s]

α_γ ≡ abundance of γ-emission of energy E_γ [γ emitted per disintegration]

ε_γ ≡ total efficiency at energy E_γ [γ detected per γ emitted]

Δ ≡ counting time [s]

D(Δ) ≡ correction for decay during measurement. Whenever $\Delta \ll t_{1/2}$, D(Δ) ~ 1 !

G(τ) ≡ correction for decay during irradiation. Whenever $\tau \ll t_{1/2}$, G(τ) ~ 1 !

$e^{\lambda t}$ ≡ correction for decay from EOB to the beginning of measurement. This term is neglected if regression fittings are adopted.

In case of a radionuclide emitting more than one γ-line (i.e: $E_{\gamma i} \Rightarrow \alpha_{\gamma i}$, $\varepsilon_{\gamma i}$; i = 1,...,r), the mean value of the t.t.y. on the various γ-energies, is sometimes calculated as:

$$(7)\quad \bar{y}(E) = \frac{1}{r}\sum_{i}^{r} y_{\gamma i}(E)\ ,\qquad (\ i = 1,\ldots,r\ )$$

Large uncertainties on emission abundances $\alpha_{\gamma i}$ can lead sometimes to large discrepancies amongst the various $y_{\gamma i}$ values. In any case, the chosen γ-emissions have to be reported together with both the chosen abundances and radionuclide half-life.

More complex equations must be used in cases when either metastable levels or radioactive chains are induced in the target, as in the case shown in Fig. 1 [4,5].

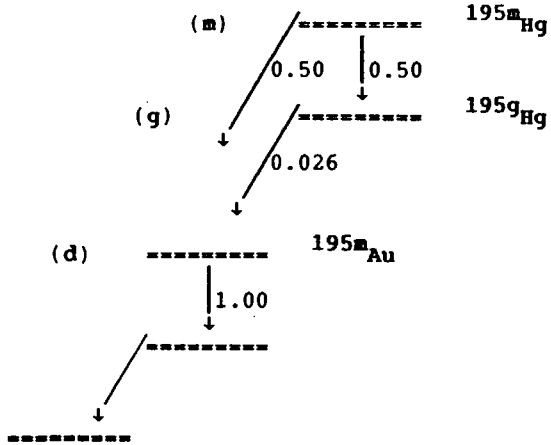


Fig. 1. Simplified decay scheme of the $^{195m,g}Hg \rightarrow ^{195m}Au$ generator, with the branching ratios used for the calculations in eq.(10)

1.2. Growth of Activity

From eq.(5), it is possible to calculate the activity h (per intensity unit) produced at the End Of a Bombardment (EOB) of generic duration τ, by integration of the following differential equation:

$$(8)\quad \dot{h}(E,\tau) = y^{EOIB}(E) - \lambda * h(E,\tau)$$

which leads to:

$$(9)\quad h^{EOB}\ [Bq\ A^{-1}\ MeV^{-1}] \equiv h^{EOB}(E,\tau) = \frac{y^{EOIB}(E)}{\lambda}\left(1- e^{-\lambda\tau}\right)$$

$$(9')\quad \equiv h^{EOSB}(E) * F(\tau)$$

where:

$h^{EOSB}(E)$ ≡ saturation activity per intensity unit [Bq A^{-1} or ... MBq μA^{-1}, GBq μA^{-1}] at energy E, at the End Of a Saturation Bombardment, EOSB , (i.e: $\tau \sim 5\ t_{1/2}$)

$F(\tau)$ ≡ growing factor

An example of the influence of irradiation time on radioisotopic contamination of ^{67}Ga by ^{66}Ga, is given in Fig. 2. In this figure is reported the behaviour of the correction factor for the ratio between the yields at the EOIB of ^{66}Ga and ^{67}Ga vs irradiation time. From this graph, calculated from eq.(9), it is possible to calculate their ratio at the EOB.

It is relevant to remember at this point that in case of short-lived radioisotopes (in the present paper: radioisotopes with half-lives of the same order of magnitude of a typical irradiation time, $t_{1/2} \sim \tau$) from the practical point of view, the saturation activity per intensity unit, h^{EOSB} is generally considered a more relevant parameter than y^{EOIB}.

Nevertheless, if either isomeric levels or decay chains are induced in the target during irradiation, kinetic laws more complex than eq. (9) have to be taken in account.

As an example, let's consider the production of the generator of USLRN $^{195m,g}Hg \rightarrow {}^{195m}Au$ via $^{197}Au(p,3n)$ nuclear reactions. The generator decays in accordance to the scheme shown in Fig. 1 [4].

The following differential equation system is effective for the three radionuclides: ^{195m}Hg (metastable, m), ^{195g}Hg (ground, g) and ^{195m}Au (daughter, d):

$$(10)\quad \begin{cases} \dot{h}_m = y_m^{EOIB} - \lambda_m * h_m \\ \dot{h}_g = y_g^{EOIB} - \lambda_g * h_g + m\,\lambda_m * h_m \\ \dot{h}_d = y_d^{EOIB} - \lambda_d * h_d + (1-m)\,\lambda_m * h_m + g\,\lambda_g * h_g \end{cases}$$

where: $m = 0.50$ ≡ branching ratio of ^{195m}Hg on ^{195g}Hg

$g = 0.026$ ≡ branching ratio of ^{195g}Hg on ^{195m}Au

Analytical solutions of the problem have been already published [5,6]. In such a case, a more complex relation than eq. (9) holds between $h^{EOSB}(E)$ and $y^{EOIB}(E)$, as it is shown in Fig. 3, which represents the behaviour of the ratio between the two isomers ^{195g}Hg and ^{195m}Hg vs irradiation time, up to saturation.

1.3. Thick-Target Yield, T.T.Y., and Activity

The reason of the relevance of t.t.y. data is concerned with the possibility of computation of T.T.Y. of a nuclear reaction - by numerical and sometimes analytical integration - as a function of both incident particle energy, E^{in}, on a "thick-target", and particle energy loss, ΔE, in the target itself [3,5].

By definition:

$$(11)\quad T.T.Y.^{EOIB}\ [Bq\ C^{-1}] \equiv Y^{EOIB}(E,\Delta E) = \int_{E^{out}=E^{in}-\Delta E}^{E^{in}} y^{EOIB}(E)\,dE =$$

$$(11')\quad = \frac{\lambda\,(N_a/M)}{Q}\int_{E-\Delta E}^{E}\frac{\sigma(E)}{S(E)}\,dE$$

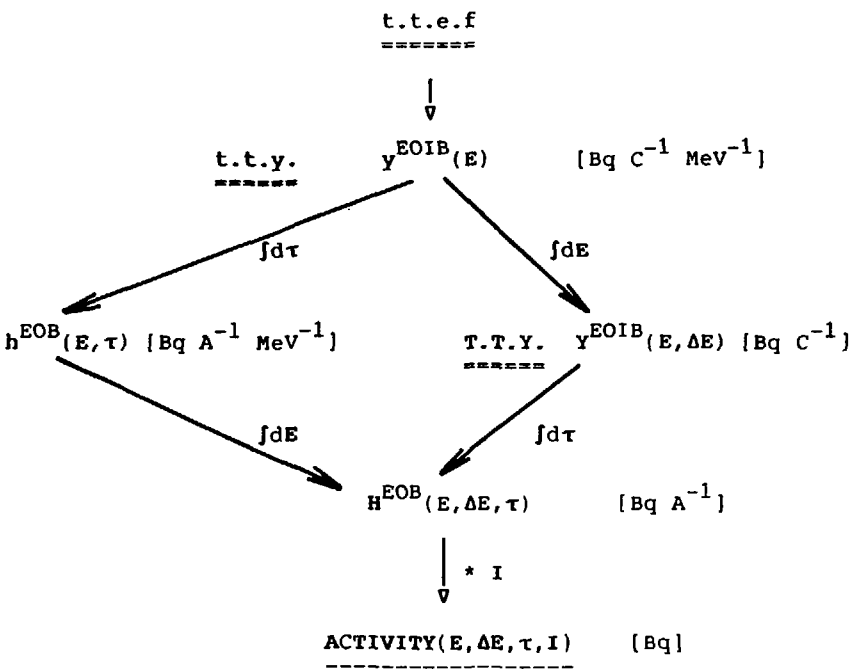
This definition holds at both EOIB and EOB, being possible the integration vs energy of both $y^{EOIB}(E)$ and $h^{EOB}(E,\tau)$:

$$(12)\quad H^{EOB}\ [Bq\ A^{-1}] \equiv H^{EOB}(E,\Delta E,\tau) = \int_{E^{out}=E^{in}-\Delta E}^{E^{in}} h^{EOB}(E,\tau)\ dE$$

and finally, the ACTIVITY which is theoretically produced at an incident energy E, with a beam intensity I, after an irradiation of duration τ on a thick target of energy loss ΔE, is given by:

$$(13)\quad ACTIVITY(E,\Delta E,\tau,I)\ [Bq] = H^{EOB}\ [Bq\ A^{-1}] * I\ [A]$$

The whole procedure can be resumed as follows:



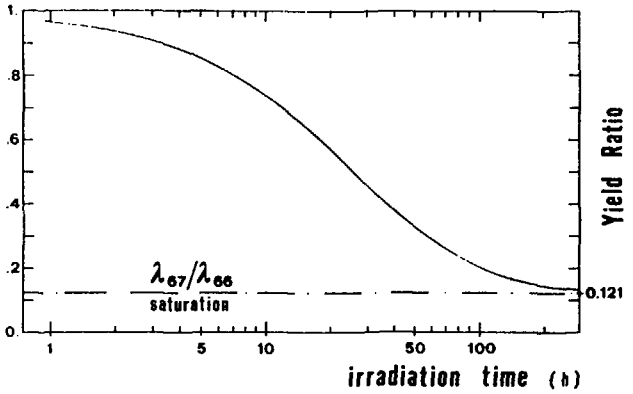


Fig. 2. Theoretical correction factor for the ratio at EOB, between the yields of ^{66}Ga and ^{67}Ga, vs irradiation time.

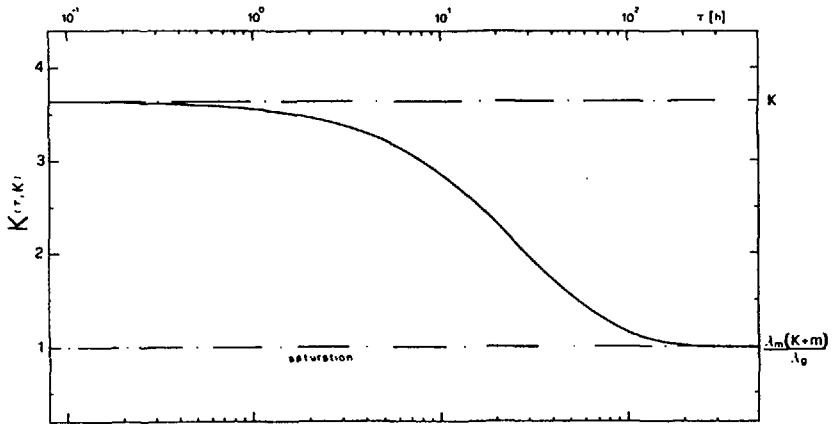


Fig. 3. Theoretical correction factor vs irradiation time for the ratio between the yields at EOIB of ^{195}Hg and ^{195m}Hg. The isomeric ratio at EOIB of 3.65 refers to the calculated optimum irradiation conditions: E = 33.5 MeV, ΔE = 13.5 MeV.

Typical results of this calculations are shown in Figs. 4 and 5, which refer to the integration of t.t.e.f. data for $^{nat}Zn(p,xn)^{66,67}Ga$ nuclear reactions [7,8], and in Fig. 6 for $^{197}Au(p,3n)^{195m}Hg$ ones [9]. On these figures, it is possible to identify the locus of the maxima of T.T.Y.s for the various couples (E,ΔE).

Similar calculations for the other mercury radionuclides ^{195g}Hg, ^{197m}Hg, ^{197g}Hg and ^{193m}Hg, make it possible the theoretical calculation of both yield and radionuclidic purity of the USLRN ^{195m}Au [9].

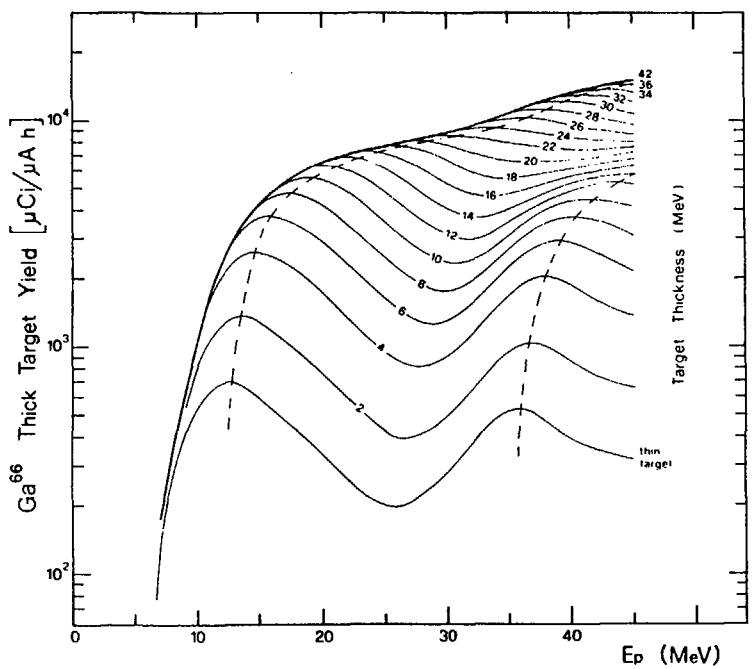


Fig. 4. THICK-TARGET YIELDS at EOIB for $^{nat}Zn(p,xn)^{66}Ga$, obtained by integration of t.t.e.f. [8] in accordance with eq. (11). The loci of the maxima of the functions $Y^{EOIB}(E,\Delta E)$ are shown.

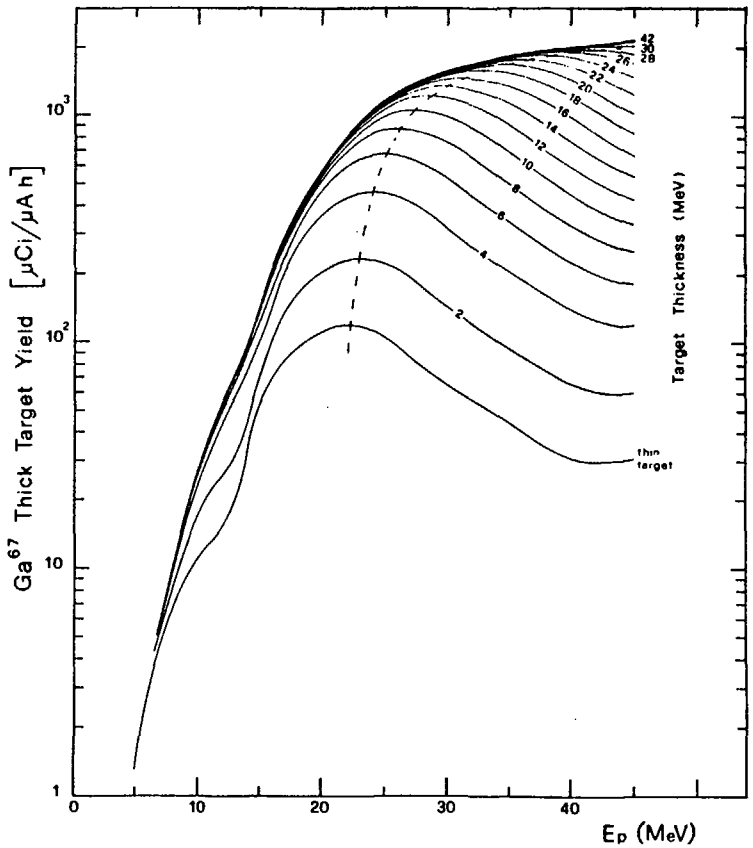


Fig. 5. THICK-TARGET YIELDS at EOIB for $^{nat}Zn(p,xn)^{67}Ga$, obtained by integration of t.t.e.f. [8] in accordance with eq. (11). The locus of the maxima of the functions $Y^{EOIB}(E,\Delta E)$ is shown.

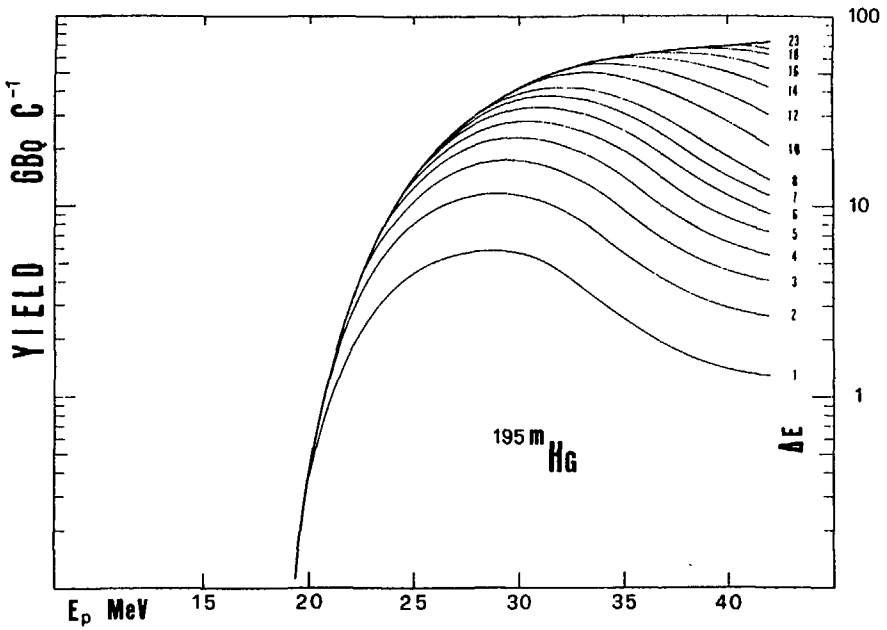


Fig. 6. **THICK-TARGET YIELD** at EOIB for the reactions $^{197}Au(p,xn)^{195m}Hg$, obtained by integration of t.t.e.f. Similar calculations made on $^{197m,g,195g,193m}Hg$ radioisotopes permit the theoretical optimization (yield and radionuclidic purity) of the production of the USLRN ^{195m}Au [9].

At last, let's define a further usefull parameter, the "instantaneous" production rate , R^{EOIB}, as the activity produced at EOIB per unit time, with a beam of intensity I :

(14) $R^{EOIB}(E,\Delta E,I) = Y^{EOIB}(E,\Delta E) * I$ [Bq s^{-1} or ... mCi h^{-1}]

Differential equations similar to eqs.(8,9) permit the calculation of production rate at EOB, R^{EOB}.

1.4. Beam Power

All the previous theoretical evaluations are made under the assumption of a linear relationship between **ACTIVITY** produced and beam intensity, eq.(13). Nevertheless, it is important to remember that the well known phenomenon of lack of this linearity for high beam intensities [10,11], does not reduce the validity of eqs.(1-14). It is well understood and experimentally verified, that the phenomenon is mainly caused by the density reduction of target atoms (mainly in gaseous and liquid phases) due to the high thermal power dissipated by the beam into the target itself [12,13].

This density reduction causes obviously a reduction of beam energy loss, ΔE, in the target and finally a decrease of the overall yield.

Furthermore, the variation in multiscattering and straggling patterns caused by density variations, makes it necessary the experimental determination of the behaviour of activity produced vs beam intensity, even if a great effort is currently made to achieve correct theoretical predictions of this phenomena [14].

In case of solid targets (either metallic or syntherized powder targets) the phenomenon mentioned above is generally negligible far away from target melting or sublimation points.

In this case, some theoretical evaluations can be made. In case of beams of light particles of charge state q , the "mean" power, P, dissipated into a target of thickness ΔE, by a beam of "mean" intensity I, is given by:

(15) P [watt] = ΔE [MeV] * I/q [μA]

In most cases, even if solid metallic targets are irradiated, the thermal dissipation is a crucial point to be taken in account [8]. In Fig. 7 is shown the theoretical behaviour of the "instantaneous" production rate R^{EOIB} of ^{67}Ga, as a function of target thickness ΔE, as well as of the power P[watt] dissipated in the target by a proton beam of intensity I[μA].

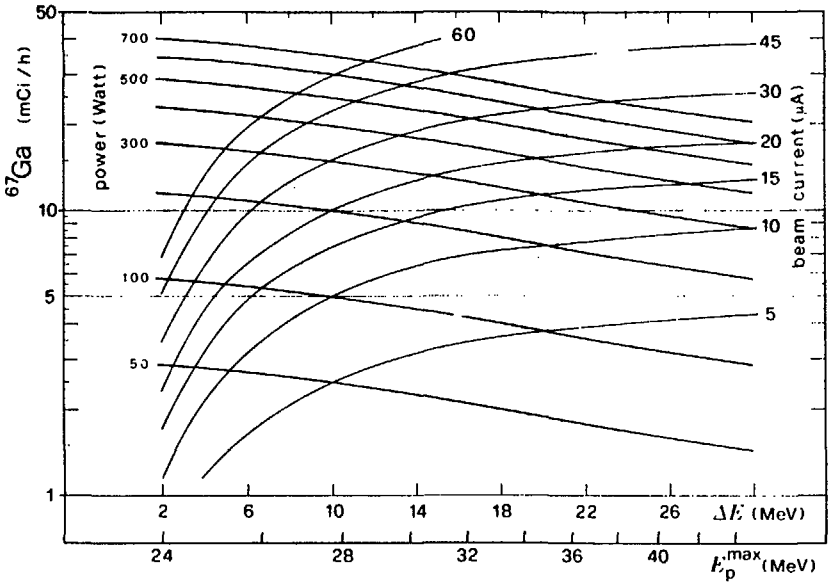


Fig. 7. Production rate at EOIB, of ^{67}Ga as a function of energy loss ΔE (MeV) and beam intensity I [μA]. If the cooling system is able to dissipate a power not higher than P [watt], the maximum production rate is given by the crossing point of P and I curves.
This point permits to identify the best Zn target thickness, ΔE and the optimum incident beam energy, E^{max} [7,8].

If P^{max} is the maximum thermal power that the system is able to dissipate avoiding target melting, and I^{max} is the maximum beam intensity obtainable from the cyclotron, the optimum target thickness to obtain the maximum production rate, R^{EOIB} [Bq s^{-1} or ... mCi h^{-1}] defined in eq.(14), is univocally found as the crossing point of power and intensity curves. The maximum R^{EOIB} value obtained in this way corresponds to a target thickness, ΔE lower than that corresponding to the highest T.T.Y. (see Fig. 5). Without this calculation, it seemed to be an obvious result that T.T.Y. increases monotonically with target thickness. Moreover, in correspondence to this optimum ΔE value, it is possible to obtain from the graph, the optimum incident proton energy, E^{max} [8].

1.5. Status of Data

In the last fifteens, many nuclear data relevant for medical radioisotope production have been experimentally determined and published by several research groups around the world. Excellent compilations and review papers have been presented in the literature in recent years [see as an ex: 15,16,17,18,19,20,21,22,23, and many others].

Anyway, some relevant data are either already unknown or published as preliminary reports only.

The following general remarks can be made:

a. To gain the best experimental data, variable energy accelerators of light charged particles (L.I: Z=1,2) are necessary, with an energy spread of the order of ± 0.1 MeV and an uncertainty on the absolute value of the "mean" energy of some tens keV (obtained by analyzing magnet or TOF calibration, as well as by use of monitor reactions) in the energy range from some MeV/nucleon to some tens MeV/nucleon (these values are typical of most cyclotrons). Energy spreads of few keV (typical of Tandem-Van de Graaf accelerators) are preferred in some cases to examine reaction fine structures [24].

b. If very reliable electronic charge integration systems are available, with an accuracy on total charge determination better than 1 %, the "single target activation technique" is recommended. The beam monitor foil technique, based on the accurate knowledge of the t.t.e.f. of a monitor reaction (ex: ^{12}C(p,pn)^{11}C or ^{63}Cu(α,n)^{66}Ga, others reviewed in this meeting), is a widely used method which leads in general to an accuracy on beam charge measurement not better than 10 %[25].

c. The use of energy absorbers (graphite, aluminium, tantalum, etc.), as well as the so called "stacked foils techni-

que" - even if necessary in some cases - induces a not tolerable **energy straggling** on the beam, that can be sometimes of the order of some MeV at the lowest energies.

Further errors are caused by the inaccuracy of range and stopping power tabulations (generally based on the Bethe-Bloch equation), being generally estimated of the order of 10 % [26,27].

In the case of non-metallic elements, both electroplated and evaporated on suitable backings,the error on target thickness determination may be sometimes of the order of some % [3,25].

d. Low beam intensities (I ~ 10-100 nA) are recommended to avoid losses by either thermal or radiolytic volatilization of both reaction products (ex: *Hg from Au targets, and *I from Te targets) and target itself (ex: metallic Hg, Te, Ge, Se, As, etc.). Target sealing with thin foils and epoxy-resins may be a further expedient to minimize losses of activity, due to both the previous phenomena and the recoil of hot reaction products.

e. High resolution gamma-spectrometry techniques with solid state semiconductor detectors are essential for off-line measurements of complex mixtures of reaction products. Certified point sources (^{226}Ra, ^{152}Eu, etc.) with overall uncertainties lower than 1.5 - 2 % are available on the market (Amersham, CEA, NBS, etc.).

Other detectors (ex: NaI(Tl)) can be used for pure emitters (ex: 0.511 MeV quanta from β^{+} emitters decay) [24].

f. **Regression fittings** of decay curves (for at least 2 or 3 half-lives) decreases further on the statistical error, increasing sharply the quality of the data.

d. **Non-statistical errors**, imputable to both nuclear decay data and stopping power/range tabulation inaccuracies, are difficult to evaluate and can lead to disagreements among the data of different authors, sometimes of the order of 10-20 %.

h. **Total errors**, evaluated as the square roots of the sums of the squares of **known** errors (target thickness, charge, activity, etc.) vary from a few percent to almost 10-20 %.

2. OPTIMIZATION

Under the assumption that the fitting of excitation functions data are unaffected by statistical and systematic errors, numerical and analytical calculations could be made in order to optimize the yield for the production of a radionuclide, minimizing at the same time the radionuclidic contamination of the radioisotope produced [3,5,7,8,9].

Under this point of view, the **T.T.Y.** with "**total energy absorption**" is a parameter with a poor practical significance, which doesn't take in account either radionuclidic purity or power dissipation considerations (see section 1.4.).

In principle, any **non-radioisotopic** contaminant might be removed after the EOB by radiochemical procedures, while the only parameters which can affect the **radioisotopic** purity are:

a. beam quality (energy spread and straggling)
b. incident energy **E** and energy loss **ΔE** in the target
c. irradiation time **τ** and waiting time **t** between EOB and the various chemical separations. The terms **E**nd **O**f **C**hemical **P**rocessing, **EOCP**, **B**eginning **O**f **C**hemical **P**rocessing, **BOCP**, are sometimes used
d. isotopic composition and chemical purity of the target
e. target composition, if non-pure elements are used.

The best compromise between high yield and high radioisotopic purity must be accepted in most cases, because the **maximum** value of the ratio:

$$R = \text{Yield} / \text{Radioisotopic Contamination} \qquad (16)$$

leads normally to an untolerable decrease of the overall yield.

In Fig. 8 is reported the behaviour of the contamination (%) of the ultra-short-lived radionuclide ^{195m}Au by other USL

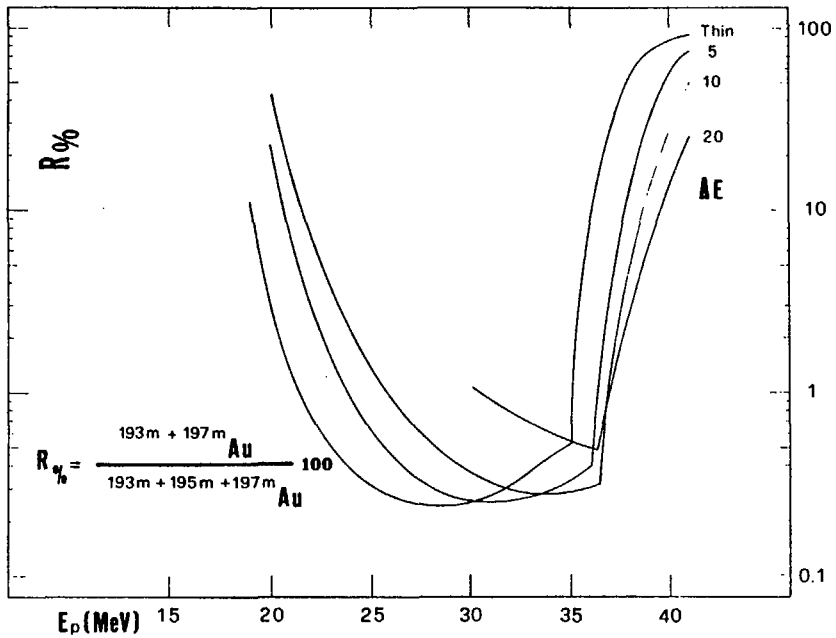


Fig. 8. Radionuclidic contamination, $R_{\%}$ of ^{195m}Au by the others USLRN ^{193m}Au and ^{197m}Au. The USLRN are supposed at the equilibrium with their mercury precursors. The contamination $R_{\%}$ is a function af both incident energy, E and energy loss, ΔE in the target.

radioisotopic contaminants (^{197m}Au and ^{193m}Au), obtained by integration of the t.t.e.f. for the $^{197}Au(p,xn)$ nuclear reactions [5,9].

It is evident from this figure, that the maximum theoretical minimization of radioisotopic contamination leads to the choice of a very thin gold target (this is an obvious result !) with an untolerable decrease of the yield of ^{195m}Au.

In this case it is advisable to impose an allowed overall contamination level based on either dosimetric or imaging quality evaluations (for ex: 0.3 %), and afterwards to choose among the various couples (E,ΔE) those leading to the maximum yield value. In the present case E^{in} = 33.5 MeV, ΔE = 13.5 MeV [9].

A different example of optimization is reported in section 1.4. and Fig. 7.

3. EXPERIMENTAL

At the Cyclotron Laboratory of the Milan University, the cyclotron production of radionuclides has been carried out since the early seventies, mainly for research purposes. In some cases (^{123}I, ^{201}Tl, $^{81}Rb \rightarrow ^{81m}Kr$, ^{67}Ga) biomedical research and clinical applications have been carried out [28-42].

A relevant fraction of research time has been devoted to the experimental determination of t.t.e.f (see Table I) in order to give a contribution to the collection of nuclear data relevant to the biomedical field. The theoretical principles expounded in section 1. have been generally respected.

The **AVF Cyclotron of the Milan University** accelerates external proton beams with energy variable from 18 to 45 MeV.

A 6 m analyzing magnet (calibrated by NMR magnetic field mesurements), as well as the $^{12}C(p,pn)^{11}C$ monitor reaction, were used to calibrate the beam energy probe. An energy spread of ± 0.1 MeV is typical.

For energies lower than 18 MeV to 5 MeV, calibrated aluminium absorbers are used with the induction of both an energy straggling of the order of 1 MeV at the lowest proton energies and an indetermination on energy due to stopping power/range calculations (main limitations of the method !). Integrated proton charges are measured under high vacuum on the Faraday cup with an error lower than 1 %. A beam spot of about 3-6 mm in diameter is typical (the activated targets can be considered as point sources for off-line γ-spectrometry measurements !).

TABLE I - Thin-target yield data for medical RI production, experimentally determined at the Milan Cyclotron Laboratory

Reactions	Radionuclides	ΔE [MeV]	Refs.
$^{nat}Te(p,xn)$	$^{121}I, ^{123}I, ^{124}I, ^{126}I, ^{128}I, ^{130}I$	9-35	28,29
$^{124}Te(p,xn)$	$^{123}I, ^{124}I$	9-30	28,29
$^{nat}Kr(p,xn)$	$^{81}Rb, ^{82m}Rb, ^{84m}Rb$	10-43	34
	$^{81}Rb \rightarrow ^{81m}Kr$	10-43	34
$^{nat}Ge(p,xn)$	$^{71}As, ^{72}As, ^{74}As, ^{76}As$	6-42	3,35
$^{nat}Tl(p,xn)$	$^{200}Pb, ^{201}Pb, ^{203}Pb$	7-43	30
(p,pxn)	^{202}Tl	7-43	30
(p,3n)	$^{201}Pb \rightarrow ^{201}Tl$	7-43	30,32,33
$^{nat}Hg(p,xn)$	$^{199}Tl, ^{200}Tl, ^{201}Tl, ^{202}Tl$	11-33	31,32,33
$^{202}Hg(p,xn)$	$^{199}Tl, ^{200}Tl, ^{201}Tl, ^{202}Tl$	13-27	32,33
$^{203}Tl(p,xn)$	$^{200}Pb, ^{201}Pb, ^{203}Pb$	14-36	32,33
(p,3n)	$^{201}Pb \rightarrow ^{201}Tl$	14-36	32,33
$^{nat}Zn(p,xn)$	$^{66}Ga, ^{67}Ga$	6-44	7*,8
(p,pxn)	^{65}Zn	6-44	7*,8
$^{nat}Pb(p,xn)$	$^{205}Bi, ^{206}Bi$	8-44	40

* in italian

TABLE II - Thin-target yield data for medical RI production, experimentally determined at Milan Cyclotron Laboratory and published in a preliminar form only.

Reaction	Radionuclides	ΔE [MeV]	Refs.
$^{nat}Ta(p,xn)$	$^{178}W, ^{179}W$	18-44	41
(p,xn)	$^{178}Ta \rightarrow ^{178m}W$	28-44	
$^{nat}Ag(p,xn)$	$^{104}Cd, ^{105}Cd, ^{107}Cd, ^{109}Cd$	4-43	36
(p,pxn)	$^{106m}Ag, ^{105}Ag$	4-43	36
(p,xn)	$^{107}Cd \rightarrow ^{107m}Ag$	4-43	37
	$^{109}Cd \rightarrow ^{109m}Ag$	4-43	37
$^{nat}Sb(p,xn)$	$^{118}Te, ^{119m,g}Te, ^{121m,g}Te, ^{123m}Te$	5-43	38*
(p,pxn)	$^{118m1}Sb, ^{120B}Sb, ^{122}Sb$	5-43	38*
(p,xn)	$^{118}Te \rightarrow ^{118}Sb$	5-43	
$^{nat}Mo(p,xn)$	$^{94}Tc, ^{95m,g}Tc, ^{96}Tc$	5-44	39
$^{197}Au(p,xn)$	$^{197m,g}Hg, ^{195m,g}Hg, ^{193m,g}Hg$	7-43	5*,6,42
(p,pxn)	$^{194}Au, ^{196m2,g}Au$	7-43	5*,6,42
(p,xn)	$^{195m,g}Hg \rightarrow ^{195m}Au$	7-43	5*,6
	$^{197m,g}Hg \rightarrow ^{197m}Au$	7-43	5*,6

* in italian

Target thicknesses are chosen in order to induce energy losses not greater than 1 MeV at the lowest proton energies.

Proton energy loss calculations are carried out in accordance with the Williamson, Boujot and Picard Tables [26] and more recently with the Ziegler et al. Handbooks [27].

For calculation of energy loss in non-monoelemental targets, a computer code named RANGE has been developed.

Q value and energy threshold calculations are based on the Mattauch et al. Mass Table (1965) [43] and more recently on the Wapstra et al. ones (1977) [44,45].

Decay schemes and data are taken from the various editions of Table of Isotopes [4,46].

In any case, the single target activation technique has been adopted, with off-line γ-spectrometry decay measurements. High resolution semiconductor detectors [Si(Li), Ge (Li) and recently HPGe], connected to MCAs (LABEN, CAMBERRA Series 80 and recently EG&G ADCAMs 918A) are used. Counting errors lower than 1 % on the net peak areas are typical.

Furthemore, regression fittings and statistical evaluations are carried out with conventional computer routines (DIGITAL PDP11/23 and VAX 8600, COMPAQ PCs).

The systems are calibrated for energy and efficiency by a point multiγ-source of ^{226}Ra (4 μCi) with a certified overall uncertainty of 1.5 % (Amersham), used in the laboratory from the early seventies as the primary standard.

Among the various data which have been only preliminarly published, let's remember those reported in Table II.

4. CONCLUSIONS

The detailed knowledge - in a wide energy range - of thin-target excitation functions of both the main nuclear reaction and those leading to the production of radionuclidic contaminants, is a fundamental requirement to optimize both yield and purity of accelerator produced radioisotopes.

High quality data permit the theoretical calculation of the thick-target yield and radioisotopic contamination, taking in account incident particle energy, energy loss in the target, irradiation and waiting times.

In general, the cross-section $\sigma(E)$, related to a well defined reaction channel has to be considered the parameter with the primary physical meaning. The "effective" production cross-section", $\sigma^*(E)$ used in case of multiisotopic targets, has to be considered with some more theoretical carefulness. In the opinion of the author, the use of thin-target yield behaviour vs energy can remove any ambiguity.

The thick-target yield has a wide practical utility whenever both incident energy, energy loss in the target and radionuclidic purity are specified. In case of short-lived radioisotopes the T.T.Y. at saturation (EOSB) is a parameter with a well recognized practical significance.

Suitable corrections of these predictions for non linearity in the activity produced vs beam intensity (due to high beam currents), as well as straggling and multiscattering phenomena, have to be taken in account in any case.

Furthermore, a review of the t.t.e.f. data experimentally determined in the last fifteens at the Cyclotron Laboratory of the Milan University has been presented. Among them, let's remember some uncommon data regarding the reactions : $^{202}Hg(p,xn)^{199-202}Tl$, $^{nat}Sb(p,xn)^{118-123}Te$, $^{nat}Ta(p,xn)^{178}W$, $^{nat}Ag(p,xn)^{105-109}Cd$, $^{197}Au(p,xn)^{193-197}Hg$, $^{nat}Mo(p,xn)^{94-96}Tc$, and the generators of USLRN $^{118}Te/^{118}Sb$, $^{178}W/^{178m}Ta$ $^{107}Cd/^{107m}Ag$, $^{109}Cd/^{109m}Ag$, and $^{195m,g}Hg/^{195m}Au$.

5. ITALIAN STATUS (1987)

Up to the 1982 the only cyclotron running in Italy was the AVF Cyclotron of the Milan University (first beam 1965). The present situation is resumed in Table III. Several machines (both Cyclotrons [C] and Tandems [T]) are either running or are going to be installed.

TABLE III - Machines (C = Cyclotron, T = Tandem) installed or going to be installed in Italy (1987), with the year of the first beam, town and main research activities. Other projects (Milano, Napoli, Roma) are not completely defined.

Machine		Year	Town	Particles	Main Fields
AVF UNIV./INFN	C[@]	1965	MILANO	p 45 MeV	NP,AP,RI NC,AA,RB
SCX MC40 JRC-Euratom	C	1983	Ispra (VARESE)	p 40 MeV d 20 α 40	RD,RI,RB AA
CGR 325 CNR	C	1985	PISA	p 16 MeV d 8	PE,PET
H.V.E.C. LNL-INFN	T	1985	Legnaro (PADOVA)	LI,HI 16 MV	NP,HIP MS
H.V.E.C. LNS-INFN	T	1987	CATANIA	LI,HI 16 MV	NP,HIP
CS UNIV./INFN	C	1989 ?	MILANO[#]	LI 100 MeV/A HI 20 MeV/A	NP,HIP[#]

Legenda:

UNIV. (University of Milano, Department of Physics), **SCX** (Scanditronix), **CGR** (CGR-MeV), **CNR** (National Research Council), **INFN** (National Institute of Nuclear Physics), **CS** (Home made Superconducting Cyclotron), **LNL** (Legnaro National Laboratory), **LNS** (Southern National Laboratory), **JRC** (Joint Research Center, Commission European Communities), **NP** (Nuclear Physics), **AP** (Applied Physics), **NC** (Nuclear and Radiochemistry), **RI** (Radioisotope Production), **AA** (Proton Activation Analysis), **PE** (Positron Emitters), **PET** (PET Studies), **MS** (Mass Spectrometry), **HIP** (Heavy Ion Physics), RB (Radiobiology), RD (Radiation Damage studies for Nuclear Fusion), **LI** (Light Ions), **HI** (Heavy Ions), **AVF** (Home made Azimutally Variable Field cyclotron), **HVEC** (High Voltage Engineering Co)

After testing in Milano the machine will be installed at the LNS and coupled to the Tandem injector,

@ The machine is going to be decommissioned and substituted by a new one.

LEGENDA

t.t.e.f. ≡ thin-target excitation function

t.t.y. ≡ thin-target yield ∝ y(E) , eqs.(1,4,6)

$\sigma(E)$ ≡ nuclear reaction cross-section , eq.(1)

$\Sigma_i p_i \sigma_i(E)$ ≡ "effective" production cross-section, eq.(4)

T.T.Y. ≡ THICK-TARGET YIELD ∝ Y(E,ΔE) , eqs.(11,11')

EOIB ≡ End Of an Instantaneous Bombardment , eqs.(5,6)

EOB ≡ End Of Bombardment , eq.(9)

EOSB ≡ End Of a Saturation Bombardment , eq.(9')

EOCP ≡ End Of Chemical Processing

USLRN ≡ Ultra-Short-Lived Radio-Nuclide

$h^{EOB}(E,\tau)$ ≡ thin-target activity per intensity unit , eq.(9)

$H^{EOB}(E,\Delta E,\tau)$ ≡ THICK-TARGET activity per "" "" , eq.(12)

beam intensity ≡ beam current

$R^{EOIB}(E,\Delta E,I)$ ≡ THICK-TARGET production rate at EOIB, eq.(14)

$R^{EOB}(E,\Delta E,\tau,I)$ ≡ THICK-TARGET production rate at EOB

ACTIVITY(E,ΔE,τ,I) ≡ Activity produced at EOB

SI ≡ International System of Units

1 [μAh] ≡ 3600 [μC]

1 [μCi μAh^{-1}] ≡ 37/3.6 [MBq C^{-1}]

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SESSION III

THEORETICAL CALCULATION

Calculation of Excitation Functions with Code ALICE

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Abstract

We illustrate the minimal input requirements necessary to use the code ALICE to predict excitation functions for light ion induced reactions up to energies of 200 MeV.

I. INTRODUCTION

The code ALICE [1-4] is a nuclear reaction code which has been written to be versatile, yet easy to be used by non-nuclear physicists. The input consists of a target/projectile plus options line, a title line, and for calculation of excitation functions, a stack of incident projectile energy lines. In this report, we shall give an example of how to perform calculations with the ALICE code and show some experimental and calculated excitation functions from published works or from preprints which the author has received from users of the ALICE code.

The ALICE code performs equilibrium (compound nucleus) decay calculations using the Weisskopf formula.[5] Precompound decay is treated by the hybrid model[6,7] approach. The logic of the code and additional references to the physics may be found in several reports[3,4] and in published articles.[8,9] The ALICE code has been used to predict product yields from the interactions of 20-140 MeV photons,[10] stopped π^-,[11] nucleons to 200 MeV,[11] deuterons, α particles and heavy ions of tens to hundreds of MeV on various targets. It has been applied to energies up to 1 GeV,[12] and is one of the most versatile codes of its type.

In Section II, we describe the input lines required to execute ALICE. In Section III, we show comparisons of calculated and experimental excitation functions for a few of the reaction types summarized above.

The ALICE code is written in FORTRAN IV and requires around 230 k-bytes to execute. It is possible to modify versions for far smaller computers. Versions have been run on PDP9, micro-VAX, and Mod-Comp computers. Instructions for input are contained in the comments cards preceding the main program, and in the several reports referred to above concerning the content and physics of the code and the options of physics available.[3,4] In this discussion, we will not describe options which include fission as a mode of de-excitation.[9]

II. INPUT TO ALICE

There are three basic input line types to use the code ALICE. We illustrate here the case of an α particle bombardment of a $^{63}_{29}Cu$ target at incident energies of 10-40 MeV in 10 MeV steps. Input line 1 is for target/projectile mass and charge; line 2 is a title line, and lines 3 et seq. are incident energy cards. To execute the above problem, the input lines would be:

```
Line 1    4.000 63.00 2.000 29.00
Line 2    Calculate alpha and 63 Cu reactions
Lines 3   10.
          20.
          30.
          40.
```

These input lines will generate product yields and particle spectra at each of the four bombarding energies. Up to 20 energies may be stacked in line 3 format. A blank line after line 3 causes a new problem to be read beginning with a new line 1; two blank cards after line 3 causes normal termination. These instructions are valid for ALICE codes updated in January 1987; earlier versions require additional parameter specification on these cards.

The example given above provides adequate input for the output specified. In fact, there are many more options which may be selected on lines 1 and 3. Included among these is the option to print a table

summarizing the excitation functions, and to plot the results on a standard output medium in semi-log format without special graphics packages. One may also elect angular distributions for nucleon induced reactions, and finer or coarser energy mesh for calculation. All input choices are described in the comments cards preceding the ALICE code. The listing usually distributed contains sample input lines, and sample output (truncated to 80 columns).

III. EXPERIMENTAL AND CALCULATED EXCITATION FUNCTIONS

We present a number of comparisons between experimental excitation functions and results calculated with ALICE. All calculations were done by users, not by the author. Many of the calculations were performed with earlier versions of the code; better results may result from the more recent versions. Nonetheless, these results tend to show how well or poorly reaction yields may be predicted via simple nuclear modeling codes.

In Figs. 1-16, we show measured and calculated excitation functions for proton induced reactions on targets of V, Mn, Fe, and Co. In Figs. 17-23, we show results for deuteron induced reactions of Co. In Figs. 24-27, we show ^{3}He induced reactions, and in Figs. 28-30 ^{4}He induced reactions, all on ^{59}Co targets. These figures are from Refs. 13-17 by R. Michel et al.

In Figs. 31-33, we show proton excitation functions on Co, Ni, Ta and Mg targets, and in Fig. 34, we show excitation functions for α induced reactions on Ag and Zn targets. Calculated results are all with the ALICE code. The results of Figs. 31-34 are due to Dr. S. J. Mills.[18,19]

Whether the calculations of ALICE are in good or poor agreement with the data is a largely subjective judgment. We can nonetheless make some comments.

Consider first the proton induced reactions of Figs. 1-16 and 31-33. The shapes of the calculated excitation functions are in quite good agreement with data over the entire energy range. The calculations therefore give a good estimate of the optimum (peak) bombarding energies. The calculated absolute cross sections are also in quite good agreement with data, except for yields of isotopes near Ni and Co. Here it has been shown that the structure of the particular nuclei (closed shell effects) has a significant influence on the yields.[20] This has been verified for a large number of experiments in this mass region,[20] and indeed the effect was predicted theoretically[21] prior to these measurements. Rosenzweig gave a prescription for treating this effect in calculations, and Mills[18,19] has followed this prescription in his calculations with ALICE given by the solid lines in Figs. 31 and 32. In this case, the cross-sections are also in quite satisfactory agreement with data.

In Figs. 17-23, excitation functions for deuteron induced reactions are shown. It is not clear that the physics of the ALICE code is appropriate for deuteron induced reactions, since the deuteron undergoes many direct "breakup" reactions (referred to as Phillips-Oppenheimer stripping and pick-up reactions) in which the full projectile energy is not transferred to a simple initial (doorway) configuration. Nonetheless, with the exception of the (d,p) channel, the model calculation does quite well in reproducing both the energy dependence and cross sections of these experiments.

Similar statements hold for the ^{3}He induced reactions of Figs. 24-27. In Fig. 26, as in Fig. 17, the one neutron transfer reaction shows the greatest problems in reconciling calculated and measured results. Even so, the model calculations provide a good guide to optimum yields for most of the reaction channels.

The one neutron transfer channel for the α induced reaction in Fig. 28 is also poorly given by ALICE, as is the likely one neutron transfer followed by proton emission in Fig. 19. The other α induced reactions are calculated reasonably well in Figs. 29 and 30. The calculations by Mills in Fig. 34 show quite good agreement with experimental yields.

IV. CONCLUSIONS

We have shown that the ALICE code with minimal input, and requiring no study of the physics involved, is useful in estimating optimum bombarding energies for many light ion induced reactions. Because the high energy tails of excitation functions are also reproduced, the code should also be useful in estimating impurity yields (see, e.g., Fig. 6). Similar comparisons would be of interest for heavy ion induced reactions.

The ALICE code is supported by manuals; input is summarized in the comment cards. A new version requires only target and projectile atomic number and mass number, and projectile energy as input. The code is written in standard FORTRAN IV, and has been implemented on micro-VAX and smaller computers. In its use, some consideration should be given to reactions which proceed by mechanisms not presently treated by ALICE; the neutron transfer reactions of d, ^{3}He and α projectiles seem to be in this category.

V. ACKNOWLEDGMENTS

The author wishes to express appreciation to Dr. R. Michel and Dr. S. J. Mills for providing the figures used in this report, and for permission to use them.

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20. M. Blann, Nucl. Phys. 80, 223 (1966).
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Figures 1-16 Calculated (ALICE) and experimental excitation functions for proton induced reactions on targets as indicated. These results are from Refs. 13 and 14. The k and n_0 values refer to ALICE precompound parameters. The default values are k=2, n_0=3 (1.21, 0.79, 1). The geometry dependent hybrid model option is preferred (e.g., Figs. 13-16).

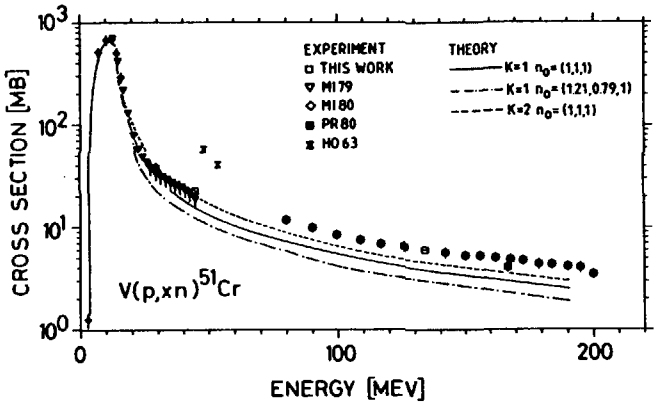


FIG. 1.

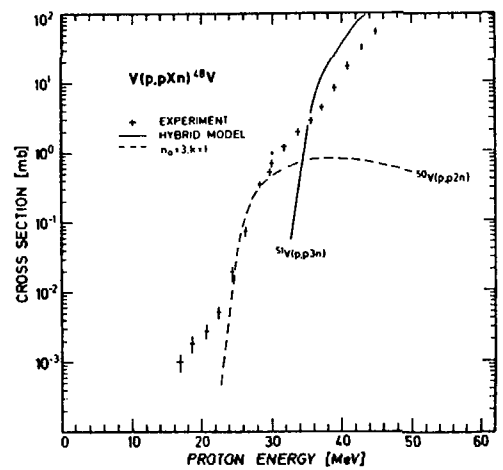


FIG. 2.

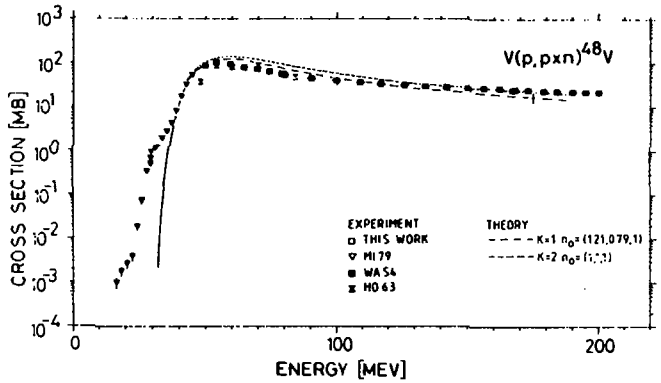


FIG. 3.

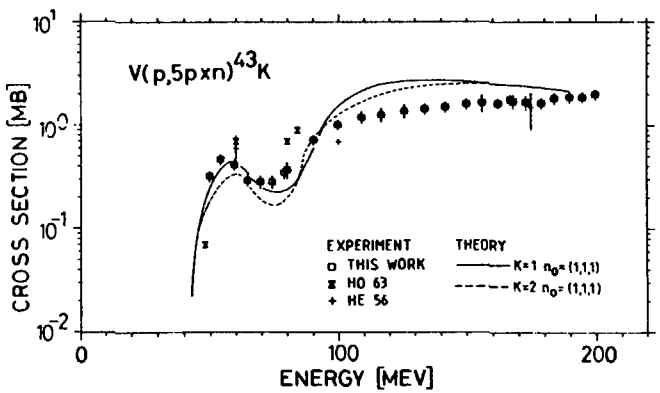


FIG. 4.

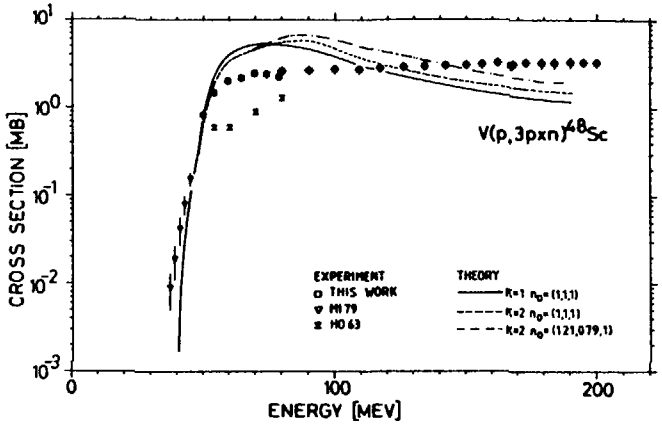


FIG. 5.

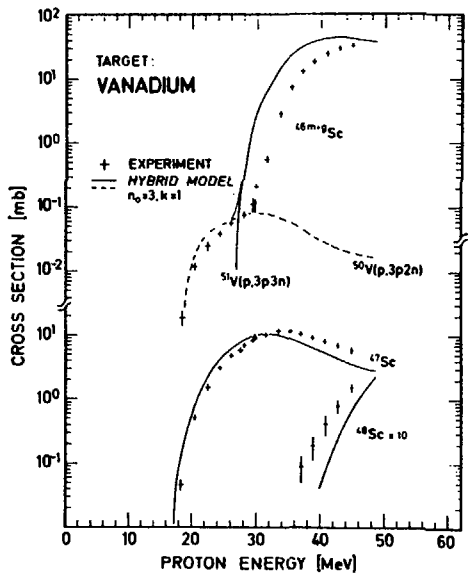


FIG. 6.

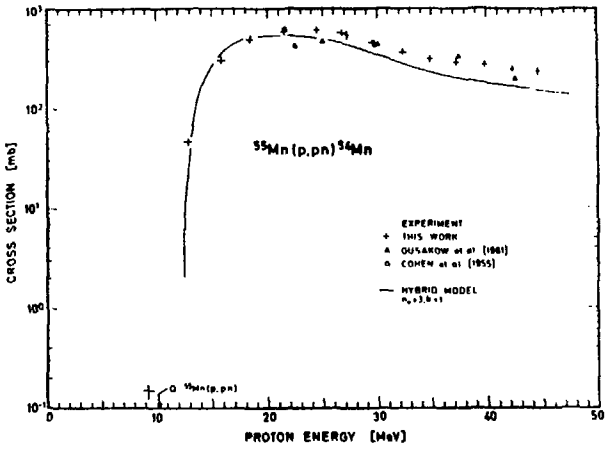


FIG. 7.

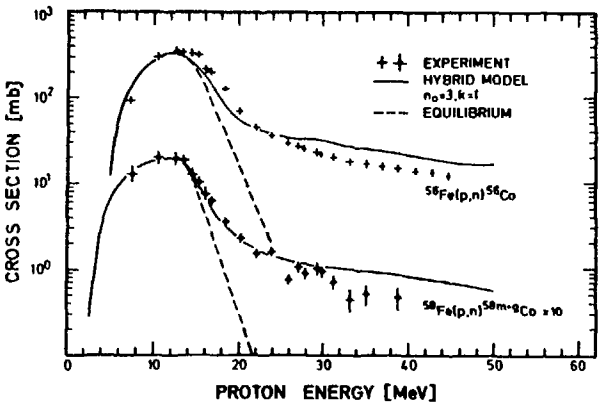


FIG. 9.

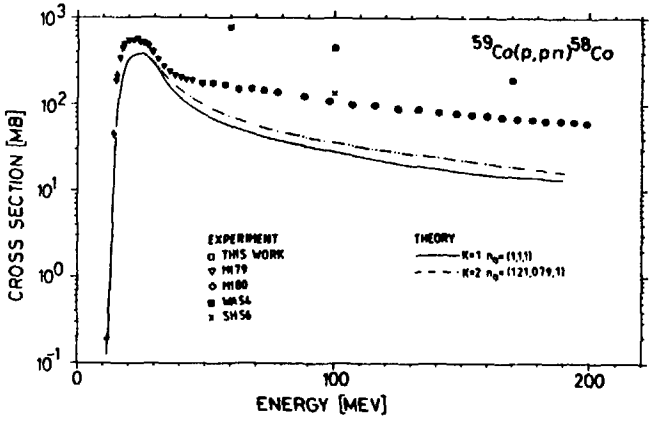


FIG. 11.

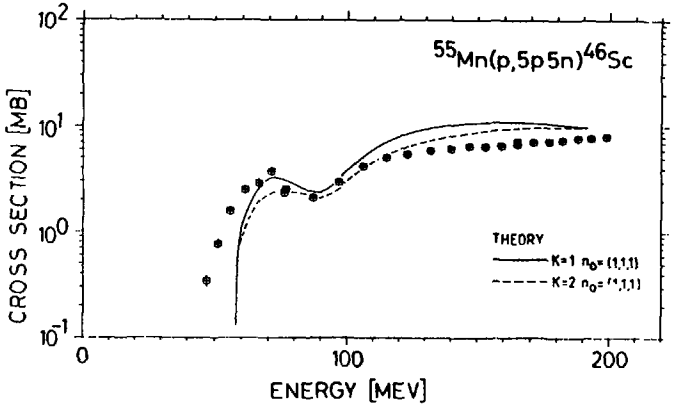


FIG. 8.

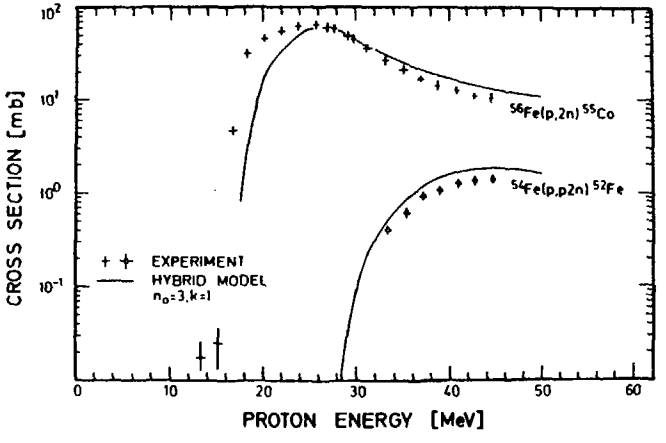


FIG. 10.

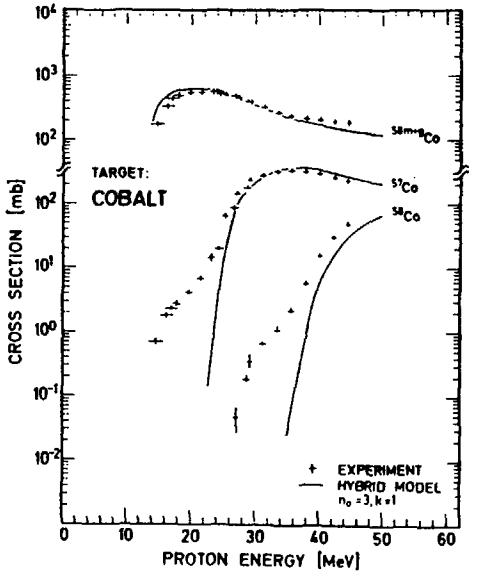


FIG. 12.

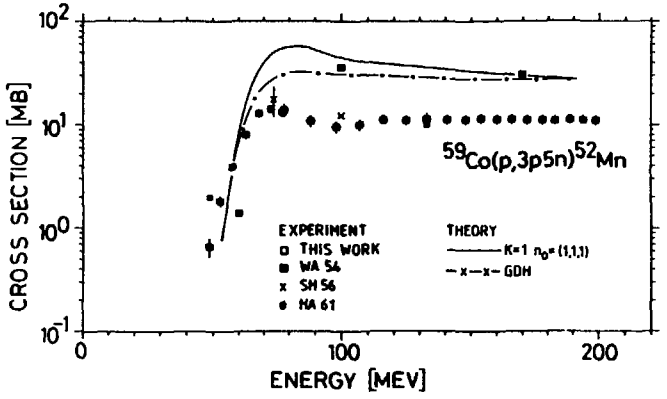


FIG. 13.

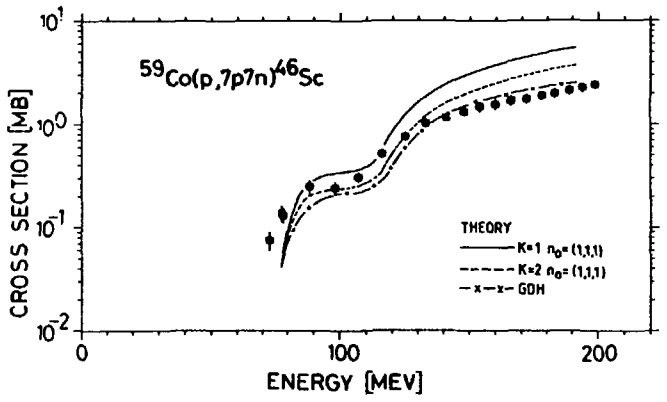


FIG. 14.

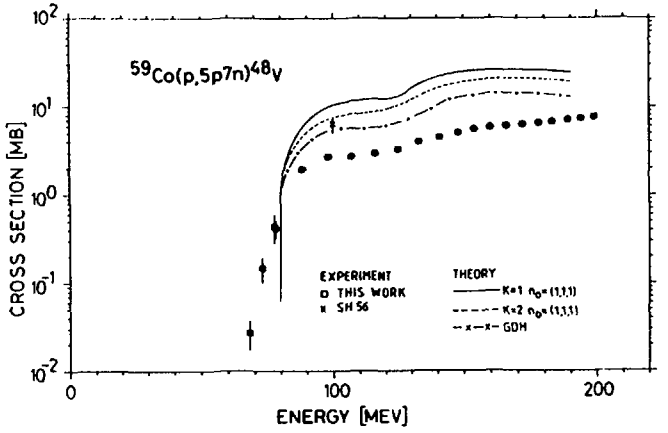


FIG. 15.

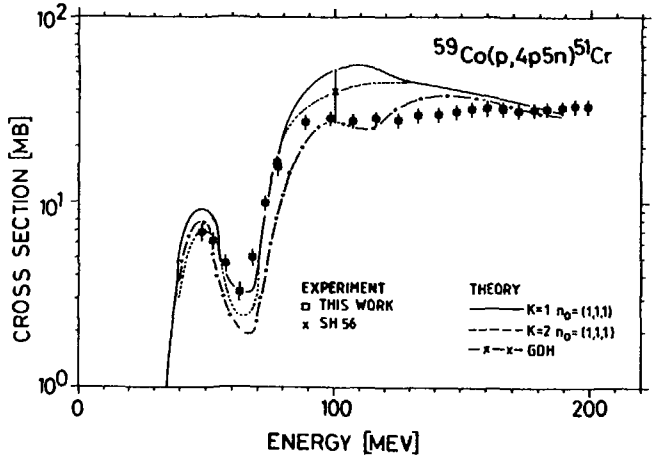


FIG. 16.

Figures 17-23

As in Fig. 1 for deuteron induced reactions. Results are from Ref. 15.

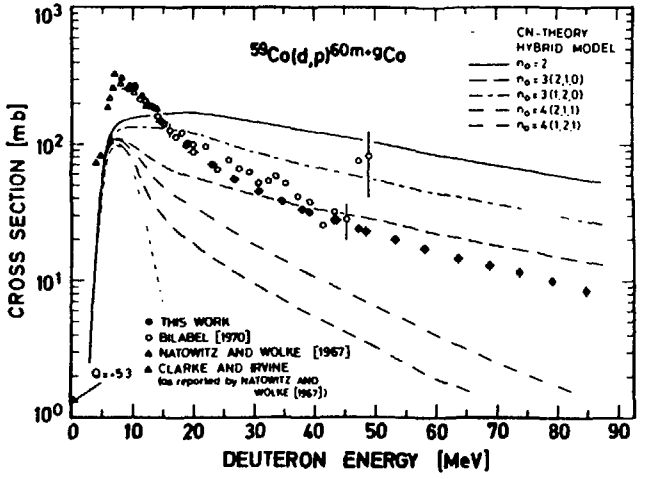


FIG. 17.

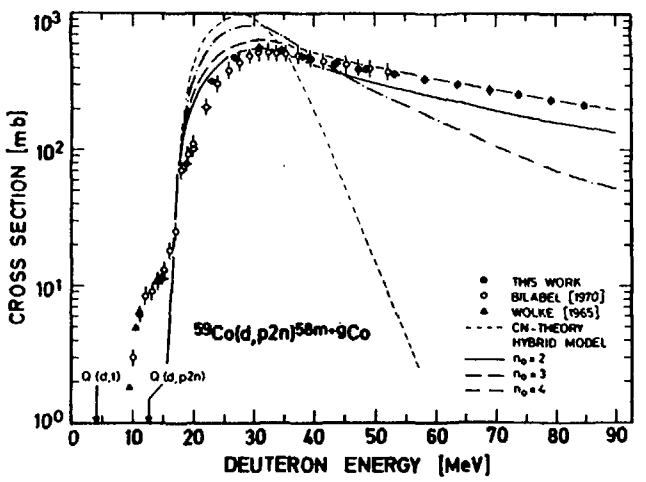


FIG. 18.

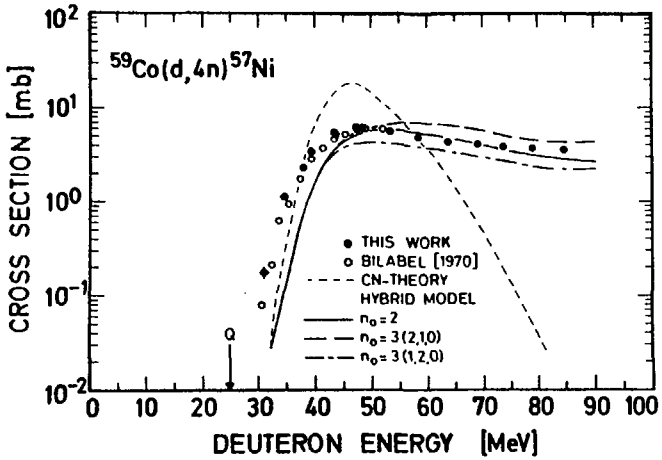


FIG. 19.

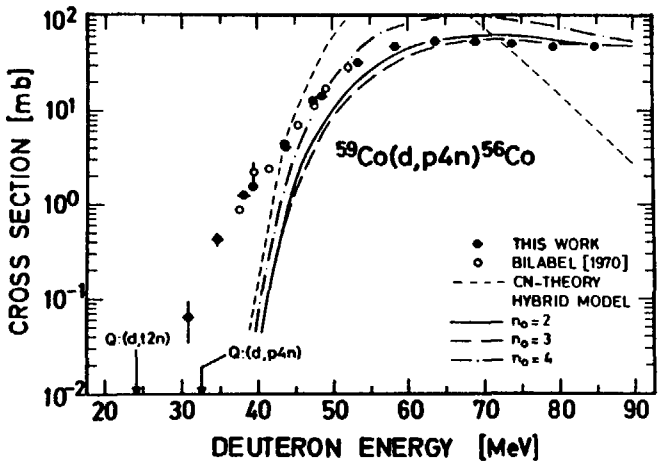


FIG. 21.

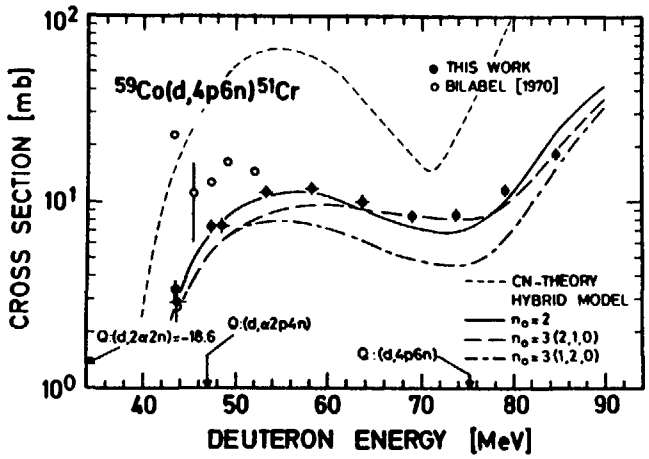


FIG. 23.

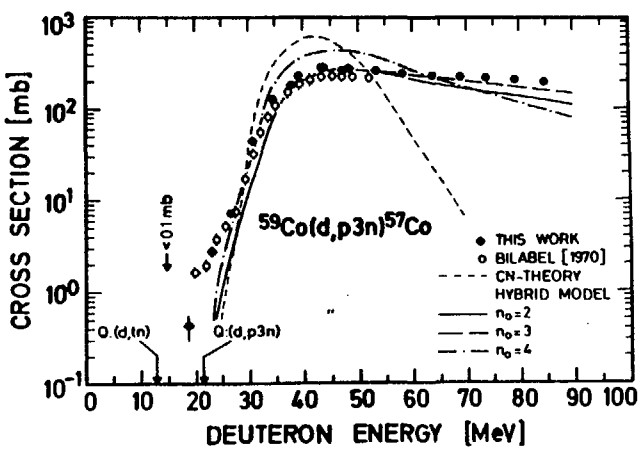


FIG. 20.

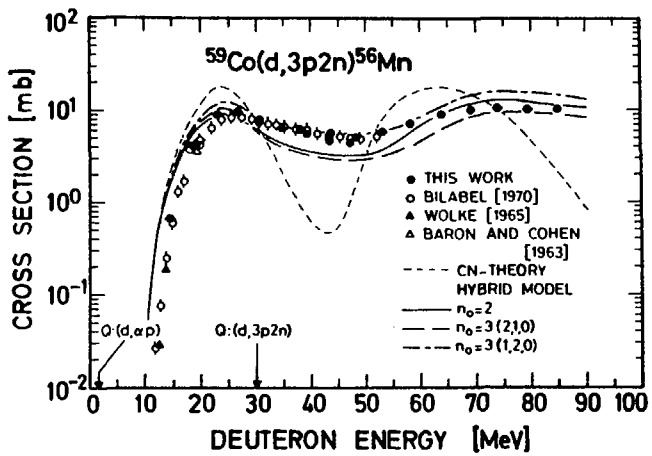


FIG. 22.

Figures 24-27

As in Fig. 1 for ^{3}He induced reactions. Results are from Ref. 16.

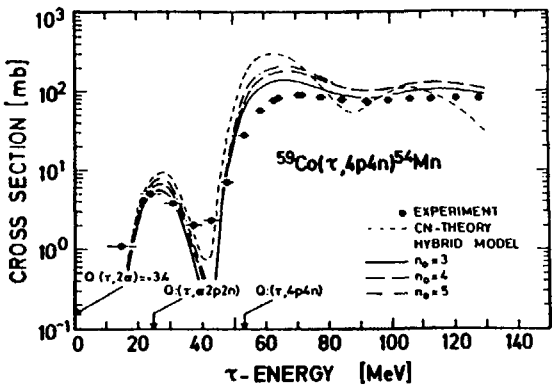


FIG. 24.

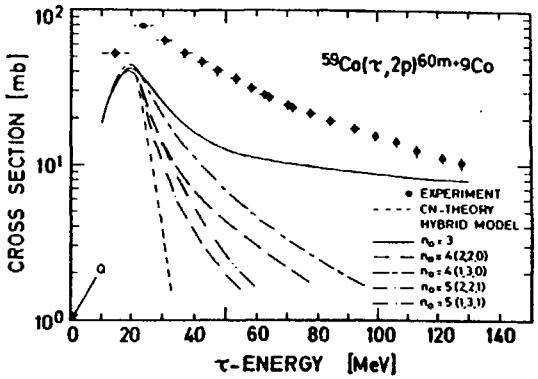


FIG. 26.

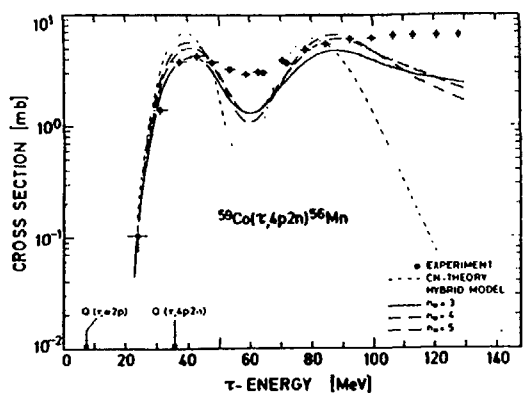


FIG. 25.

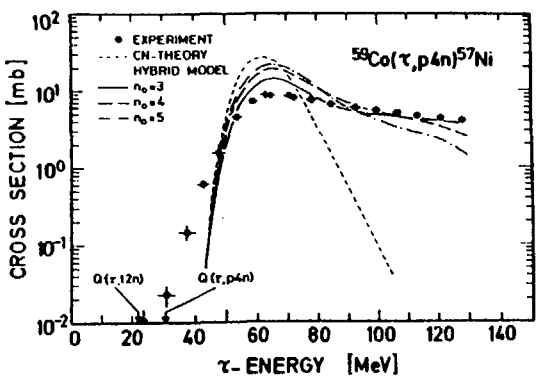


FIG. 27.

Figures 28-31

As in Fig. 1 for α induced reactions. Results are from Ref. 17.

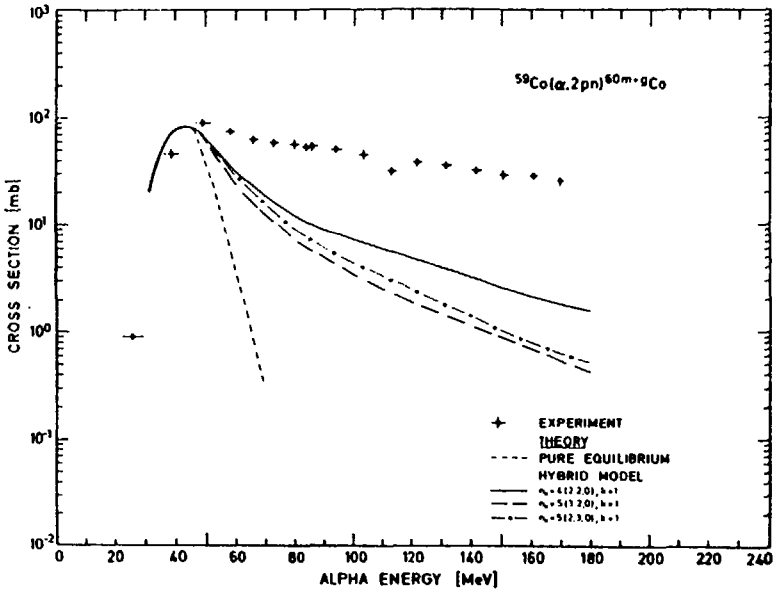


FIG. 28.

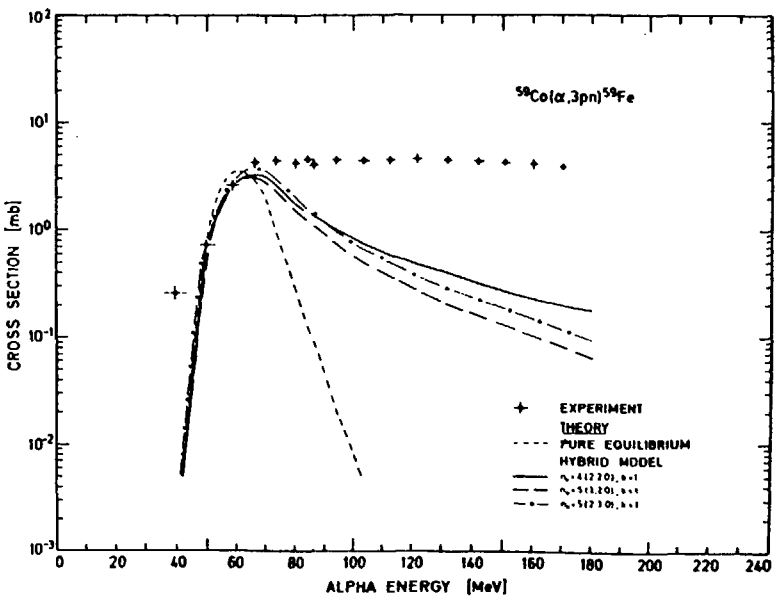


FIG. 29.

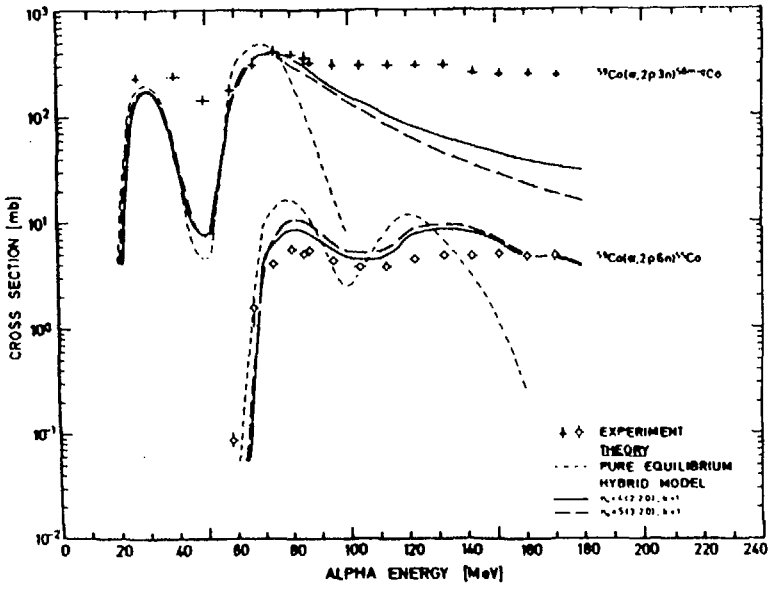


FIG. 30.

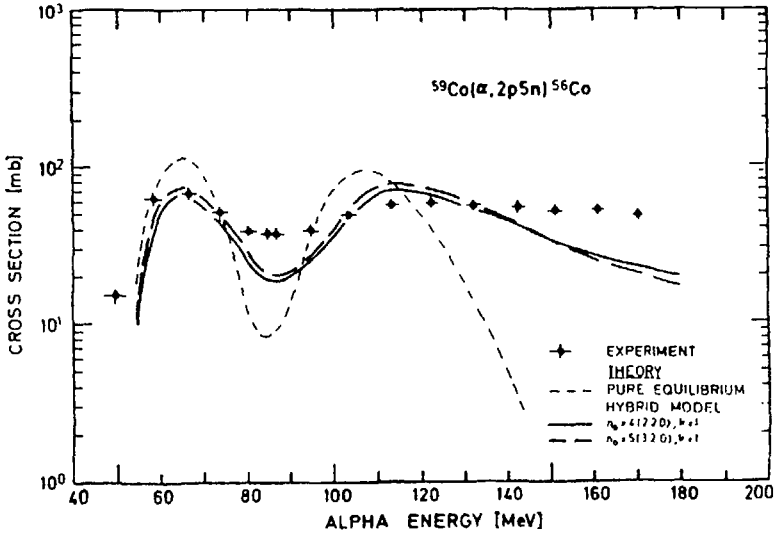


FIG. 31.

Figures 32-35

p and α induced reactions from Refs. 18 and 19. For α induced reactions, n_0=4 (2,2,0) was used (two proton excitons, two neutron excitons and no holes).

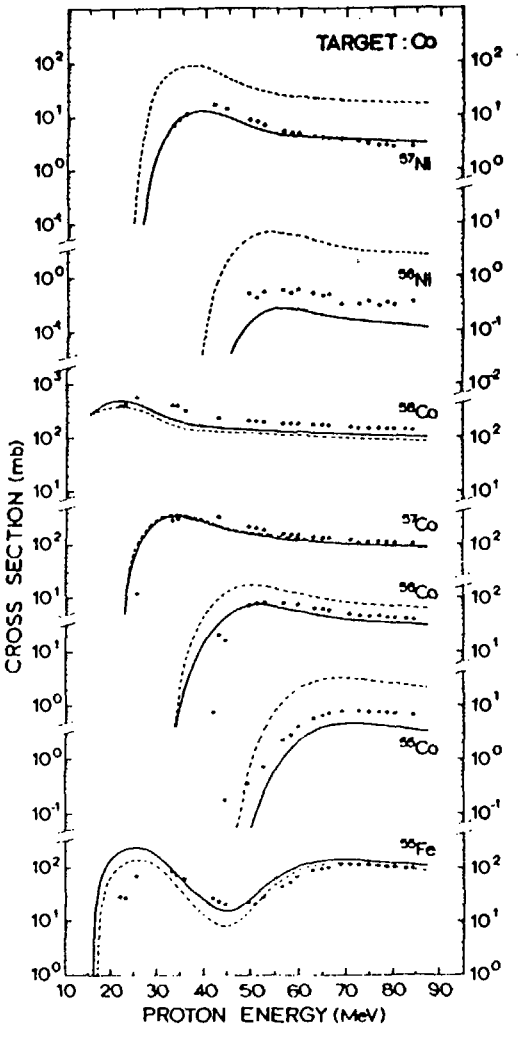


FIG. 32.

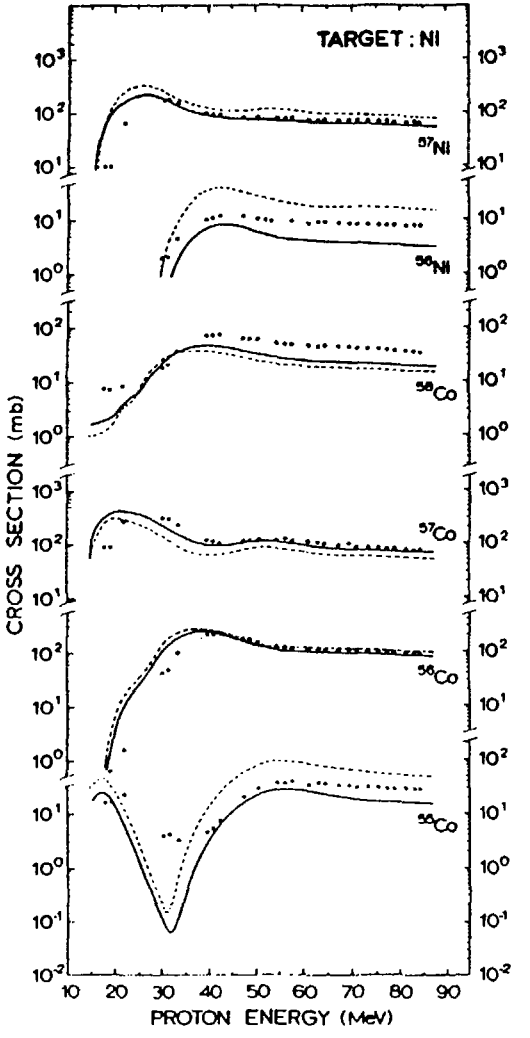
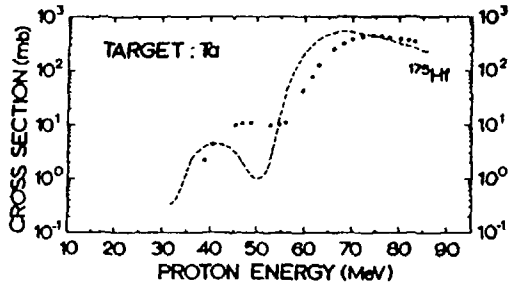
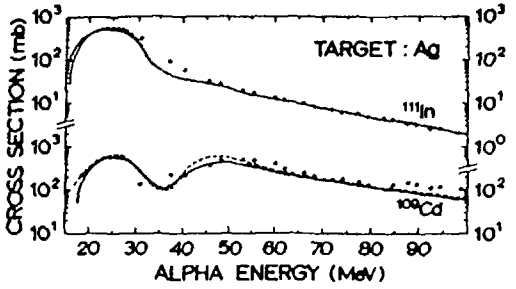


FIG. 33.





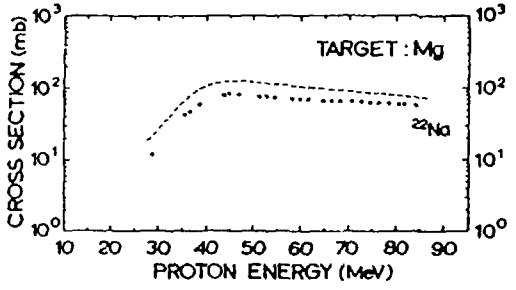


FIG. 34.

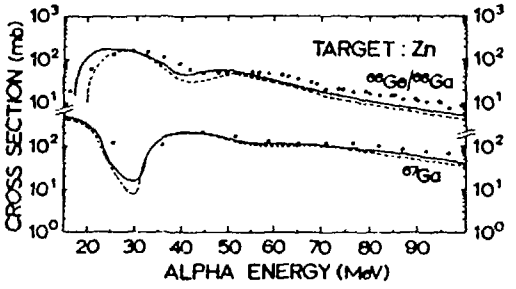


FIG. 35.

CALCULATION OF EXCITATION FUNCTIONS FOR RADIOISOTOPE PRODUCTION

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Abstract: Computer codes based on nuclear reaction models have become a means to estimate cross sections if experimental data are missing. The relevant models are introduced and their applicability is discussed. Excitation functions for proton and alpha-particle induced reactions, calculated with the code STAPRE are presented and compared with experimental results.

Introduction

Amongst the several types of nuclear data relevant for the medical application of radioisotopes (cf. Ref. 1) cross section data are needed in connection with the production of radioisotopes. Though the optimum production conditions for radioisotopes depend on many factors, excitation functions are important to determine the incident particle energy range required for the optimum production of a specific radioisotope and to calculate thick target yields both for the required radioisotope and possible contaminants for specific irradiation conditions. As pointed out in several papers /1,2,3/ the cross section is the basic parameter in the production of an isotope, which cannot be substituted completely by experimental thick target yield information. Although excitation functions are only the beginning in finding optimal conditions for radioisotope production, they seem to be absolutely necessary for a better understanding of the relationship between the various factors contributing to product and contaminant yield. In contrast to the experimental data base for neutron induced reactions relatively few measurements of excitation functions for the medical important charged particle induced reactions exist.

For reactions and/or energy ranges where no experimental data are available the application of nuclear reaction theory seems to be a feasible method to get more information on the data required. A number of nuclear model codes were developed first to gain theoretical understanding of the nuclear reaction processes involved. Later they have been also used successfully in cross section evaluations, mainly for neutron induced reactions (e.g. /4,5/). Also a number of authors (e.g. /3, 6-13/) had used nuclear model codes to calculate excitation functions for charged particle induced reactions of medical interest and compared their results with experimental ones.

We first introduce the nuclear reaction models in use for the calculation of excitation functions. Then we discuss their applications and finally we present results obtained with the code STAPRE compared with experiments.

Nuclear Reaction Models

Most of the computer codes in use to calculate excitation functions employ a combination of the compound nucleus evaporation model and a model for preequilibrium emission.

The compound nucleus evaporation model is based on Bohr's concept of the compound nucleus /14/, which decay is assumed to be independent from its formation. The cross section formulae resulting thereof depend on the conservation laws taken into account. Taking into account energy conservation only leads to the calculational method first proposed by Weisskopf and Ewing /15/. The energy differential cross section for a binary reaction A(a,b)B characterized by the incident particle energy ϵ_α in the entrance channel α and by the outgoing particle energy ϵ_β in the exit channel β is given by

$$\sigma_{\alpha\beta}(\epsilon_\alpha,\epsilon_\beta) = \sigma_\alpha(\epsilon_\alpha)\frac{\Gamma_\beta(E,\epsilon_\beta)}{\Gamma(E)}\omega_\beta(U) \qquad (1)$$

with $\Gamma_\beta(E,\epsilon_\beta)$ the decay width into the channel β and $\Gamma(E)$ the total decay width of the compound nucleus with excitation energy E. The cross section for the formation of the compound nucleus is $\sigma_\alpha(\epsilon_\alpha)$; $\omega_\beta(U)$ is the density of excited states of the residual nucleus around the excitation energy U. Under assumption of time reversal invariance the branching ratio Γ_β/Γ can be evaluated in terms of the inverse cross sections $\sigma_\gamma(\epsilon_\gamma)$ for the formation of the compound nucleus in all open channels.

$$\frac{\Gamma_\beta(E,\epsilon_\beta)}{\Gamma(E)} = \frac{(2i_\beta+1)\,k_\beta^2\sigma_\beta(\epsilon_\beta)}{\sum_\gamma (2i_\gamma+1)\int_0^{E-S_\gamma} d\epsilon_\gamma k^2{}_\gamma\sigma_\gamma(\epsilon_\gamma)\omega_\gamma(U)} \qquad (2)$$

where i_γ is the spin of the lighter fragment and k_γ the wave number corresponding to channel energy ϵ_γ and S_γ the particle separation energy in the channel γ. Activation cross sections are then calculated by summing up the cross sections leading to excitation energies U of the residual nucleus below the particle emission threshold.

Taking also spin and parity conservation into account leads to the Hauser-Feshbach formula /16/ which evaluates cross sections in terms of the optical model transmission coefficients. For entrance channel α, exit channel β and total angular momentum I and parity Π of the compound nucleus the Hauser-Feshbach formula reads

$$\sigma_{\alpha\beta}^{I\Pi} = \frac{\pi}{k_\alpha^2}\, g^I \frac{T_\alpha T_\beta}{\Sigma T_\gamma} \qquad (3)$$

The denominator comprises the sum of the transmission coefficients for all open channels, g^I is the statistical factor. The cross section for the formation of a state (U,I',Π') of the residual nucleus is then given by

$$\sigma(\epsilon_\alpha;U,I',\Pi') = \frac{\pi}{k_\alpha^2}\sum_{I,\Pi} g^I \frac{\Sigma T_\alpha T_\beta}{\Sigma T_\gamma}\,\rho(U,I',\Pi') \qquad (4)$$

where $\rho(U,I',\Pi')$ is the density of levels around U with quantum numbers (I',Π'). The summations over intermediate angular momenta and parities I,Π as well as over channel spins and orbital angular momenta are restricted by angular momentum and parity conservation. Photons can be included in the Hauser-Feshbach formalism in the same way as particles with transmission coefficients depending on the type of

electromagnetic multipole radiation. Therefore computer codes depending on the Hauser-Feshbach formula can treat gamma ray competition with particle decay properly.

As one of the current preequilibrium models we want to quote the exciton model first proposed by Griffin /17/. The states of the composite system are characterized only by the excitation energy and the number of excited particles and excited holes, which are collectively called excitons. Starting from an initial particle hole configuration the system equilibrates through a series of two body interactions which may change the exciton number by +2,0,-2 corresponding to the creation, scattering and annihilation of a particle hole pair. In competition with this internal transitions particles can be emitted from each state. These processes are described by transition rates averaged over all states of a particle hole configuration; $\lambda^-(n)$, $\lambda^\circ(n)$, $\lambda^+(n)$ for internal transitions with a change in the exciton number by -2,0, and +2, respectively, and $\lambda^e(n)$ for particle emission. Cross sections are then calculated according to

$$\sigma_{\alpha\beta}^{Pre}(\varepsilon_\alpha,\varepsilon_\beta) = \sigma_\alpha(\varepsilon_\alpha) \sum_{k=0}^{K} \sum_{n} b^{(k)}(n) \frac{\lambda_\beta^e(n,\varepsilon_\beta)}{\lambda(n)} \qquad (5)$$

with $\sigma_\alpha(\varepsilon_\alpha)$ the cross section for the formation of the composite system, $\lambda(n)$ the sum of λ^-, λ°, λ^+ and λ^e for an n-exciton configuration, $\lambda_\beta^e(n,\varepsilon_\beta)$ the particle emission rate for channel β with energy ε_β and $b^{(k)}(n)$ the population probability of an n-exciton configuration after k internal transitions which is calculated according to

$$b^{(k)}(n) = b^{(k-1)}(n+2)\frac{\lambda^-(n+2)}{\lambda(n+2)} + b^{(k-1)}(n)\frac{\lambda^\circ(n)}{\lambda(n)} + b^{(k-1)}(n-2)\frac{\lambda^+(n-2)}{\lambda(n-2)} \qquad (6)$$

With increasing number of internal transitions k the ratio $b^{(k-1)}(n)/b^{(k)}(n)$ becomes independent from k and n. This is used to derive an upper limit K for the number of internal transitio. ; taken into account for the calculation of the preequilibrium contribution of cross sections.

As another preequilibrium model we want to quote the hybrid model /18/ and its extension the geometry dependent hybrid model /19/ which are used by the code ALICE. It combines aspects of the Harp-Miller-Berne model /20, 21/, which performs a very detailed treatment of the equilibration process and the simple exciton model. The energy differential cross section for emitting a nucleon is given by

$$\sigma_{\alpha\beta}^{Pre}(\varepsilon_\alpha,\varepsilon_\beta) = \sigma_\alpha(\varepsilon_\alpha) \sum_{\substack{n=n_o \\ (\Delta n=2)}}^{\bar{n}} P_\beta(\varepsilon_\beta,n) \qquad (7)$$

$$P_\beta(\varepsilon_\beta,n) = {}_nP_\beta \left(\frac{\rho_n(\varepsilon_\beta,U)}{\rho_n(E)}\right) g\left(\frac{\lambda^c(\varepsilon_\beta)}{\lambda^c(\varepsilon_\beta)+\lambda^+(\varepsilon_\beta)}\right) D_n \qquad (8)$$

with ${}_nP_\beta$ the number of excited particles of particle type β in an n exciton state, $\rho_n(E)$ the exciton state density, $\rho_n(\varepsilon_\beta,U)$ the density of states with n excitons, such if one is emitted it would have channel energy ε_β, g the single particle state density and D_n the fraction of the initial population which has survived decay from simpler states. The emission rate of a particle into the continuum is denoted by $\lambda^c(\varepsilon_\beta)$; $\lambda^+(\varepsilon_\beta)$ is the intranuclear transition rate for a particle which would have channel energy ε_β if emitted into the continuum. The sum in equation (7) has to be taken from the initial exciton number n_o to the equilibrium value $\bar{n}$. The transition rates of the hybrid model are conceptionally different from the exciton model ones, they refer to the individual particle, rather than to the nulceus as a whole.

Application of nuclear model codes

Nuclear model codes which perform Hauser-Feshbach calculations are more complex and time consuming than ones performing Weisskopf-Ewing calculations. Angular momentum and parity conservation are essential near threshold where only a few levels with specific spin and parity contribute and the competition of gamma decay with particle emission should be taken into account to get reliable results. Therefore Hauser-Feshbach calculations are preferable for low incident

particle energies up to about 20 MeV. For higher energies the faster and simpler Weisskopf-Ewing calculations are suitable. An approximate treatment of angular momentum conservation is possible by employing the "s-wave approximation" /22/ which assumes the spin distribution of the compound nucleus to hold for all residual nuclei too. For the calculation of isomeric state production cross sections the Hauser-Feshbach formalism is indispensable.

Nuclear reaction model codes employing the compound nucleus model and a model for preequilibrium emission have been successfully applied to calculate excitation functions of nuclear reactions with neutrons, protons and alpha particles both in entrance and exit channel. They are not so well suited for the calculation of cross sections of deuteron and ^{3}He induced reactions as direct reaction mechanisms important for the weakly bound particles are not considered by them. The emission of deuterons, tritons and ^{3}He-particles may be considered in the frame of a phenomenological model by Kalbach /23/.

The applicability of the models discussed is limited in the case of light nuclei. For nuclei with mass numbers less than about 20 reliable predictions of excitation functions cannot be expected, due to the individual character of most light elements.

As pointed out by Uhl /24/ theoretical calculations cannot replace experiments at all as the model parameters like optical model parameters, level density parameters and preequilibrium model parameters need adjustment to experimental data to supply results with sufficient accuracy. To obtain accurate results each calculation of unknown cross sections should be based on parameters which simultaneously reproduce available experimental data in the mass region of interest. The degree of the agreement may then give an estimate for the accuracy of the unknown cross sections.

Calculation of excitation functions with the code STAPRE

The code STAPRE /25/ employs the exciton model for first chance preequilibrium emission. The particle hole state densities are calculated by the formula of Williams /26/. For the particle emission rates neutron-proton distinguishability as proposed by Gadioli et al. /27/ and alpha cluster preformation /28/ can be considered in the case of nucleon induced reactions. For the internal rates the expression of Williams /29/ combined with Kalbach-Cline's /30/ expression for the dependence of the matrix element of the residual interactions from the energy and mass is used. The normalisation constant for this matrix element is an adjustable input parameter of the code. As the exciton model does not consider angular momentum and parity, it is assumed that preequilibrium particle emission leads to the same spin and parity distribution in the residual nucleus as the equilibrium one. For the equilibrium stage the evaporation of neutrons, protons, alpha particles and deuterons under consideration of gamma-ray cascades can be taken into account, employing the Hauser-Feshbach formalism. The optical transmission coefficients for particles have to be supplied as input. For the transmission coefficients for photons the Brink-Axel model /31, 32/ and the Weisskopf model /32/ are employed for E1 radiation and other multipole-types, respectively. Level densities are calculated in the frame of the back-shifted Fermi-gas model /34/, low lying discrete levels have to be specified by excitation energy, spin and parity.

We used the code STAPRE to calculate excitation functions for proton and alpha-particle induced reactions for incident particle energies up to 30 MeV. The set of model parameters used, was originally established to calculate a number of cross sections for neutron induced reactions on Cr, Mn, Fe and Ni /4, 5/. The evaporation of neutrons, protons and alpha particles was taken into account. The underlying parameter set was originally adjusted to reproduce a variety of cross sections in the mass region investigated (see Ref. 5 for details). Also experimental information on level densities and particle emission spectra were used to check the parameter set. No additional adjustments were done in the course of this work.

As a first example we calculated the excitation function for the reaction ^{56}Fe(p,2n)^{55}Co. The isotope ^{55}Co is a positron emitter with 17.5 h half-life /35/ which usefulness in nuclear medicine was reported in Ref. 36. The reaction ^{56}Fe(p,2n)^{55}Co is the only relevant one for the production of ^{55}Co by bombarding targets of natural iron (^{54}Fe: 5.8%, ^{56}Fe: 91.8%, ^{57}Fe: 2.15%, ^{58}Fe:0.29% /35/) with protons

up to 30 MeV. The calculated excitation function compared with the experimental results of Lagunas-Solar and Jungermann /36/ and of Jenkins and Wain /37/ is shown in Fig. 1. We also calculated the effective cross sections for the production of the contaminants ^{56}Co and ^{52}Mn.

The reactions considered are listed in Table 1. The results are compared with effective cross sections derived from the thin target yield figures of Ref. 36. Also the contributions of the dominant reactions compared with experimental data from Ref. 37 are shown in Figs. 2 and 3.

As another example we calculated the cross sections for the $^{52}Cr(p,n)^{52m+g}Mn$ reactions. The results are compared with the experimental values given by Lindner and James /38/ and by Wing and Huizenga /39/ in Fig. 4.

The chromium isotope ^{51}Cr (half-life 27.70 d) has been in use in nuclear medicine since 1950. This isotope and the more suitable /40/ ^{48}Cr (half-life 21.56 h) can be produced by bombarding titanium (natural isotopic composition: ^{46}Ti: 8.2%, ^{47}Ti: 7.4%, ^{48}Ti: 73.7%, ^{49}Ti: 5.4%, ^{50}Ti: 5.2%) with alpha-particles. The reactions taken into account for the calculation with the code STAPRE are summarized in Table 1. In Fig. 5 the calculated results are compared with the experimental data of Weinreich et al. /40/. In the low energy range (below the $^{49}Ti(\alpha,2n)$ threshold) the results of Vonach et al. /41/ and Chang et al. /42/ for the $^{48}Ti(\alpha,n)$ reaction are included.

In the examples given the calculations reproduce experimental results within 30-40%. This is comparable with the scattering of the experimental results of different authors. Experimental uncertainties, if given by the authors, are (with the exception of the precise measurement of Ref. 41 with 3% error) between 7 and 15% and there is also an uncertainty in the energy scale. Whenever uncertainties were given they are indicated by error bars in the figures.

Table 1 Nuclear reactions considered for the calculation of effective cross sections with the code STAPRE

Residual Nucleus	Nuclear reactions
^{48}Cr	$^{46}Ti(\alpha,2n)$
	$^{47}Ti(\alpha,3n)$
^{51}Cr	$^{48}Ti(\alpha,n)$
	$^{49}Ti(\alpha,2n)$
	$^{50}Ti(\alpha,3n)$
^{52}Mn	$^{54}Fe(p,2pn)$
	$^{56}Fe(p,\alpha n)$
^{56}Co	$^{56}Fe(p,n)$
	$^{57}Fe(p,2n)$

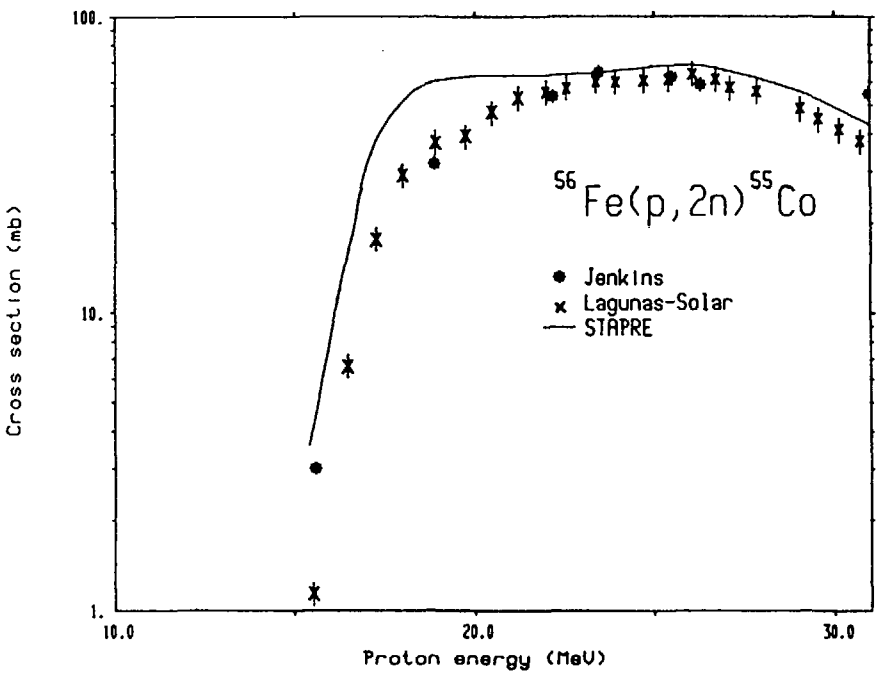

Figure 1 Calculated cross sections for the reaction $^{56}Fe(p,2n)^{55}Co$ compared with experimental results

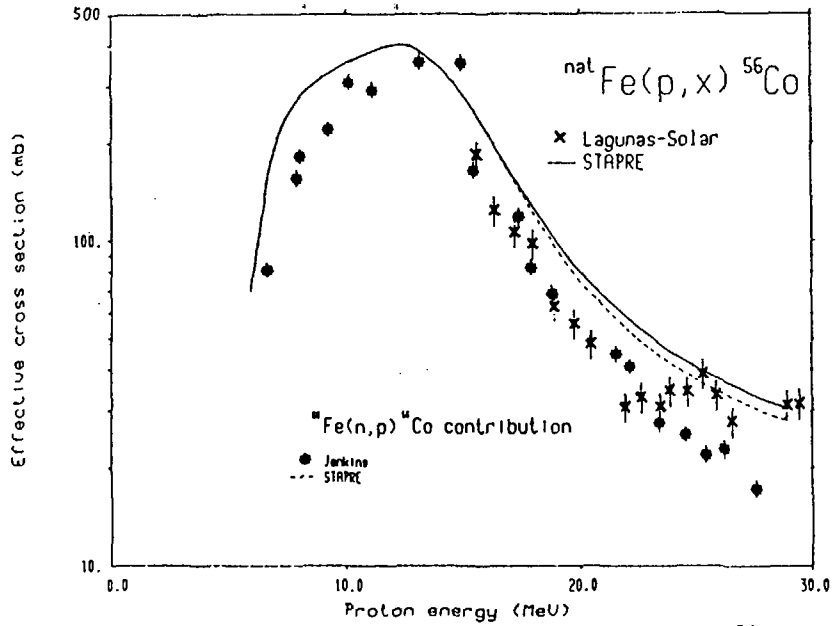

Figure 2 The calculated effective cross section for $^{nat}Fe(p,x)^{56}Co$ compared with experimental results

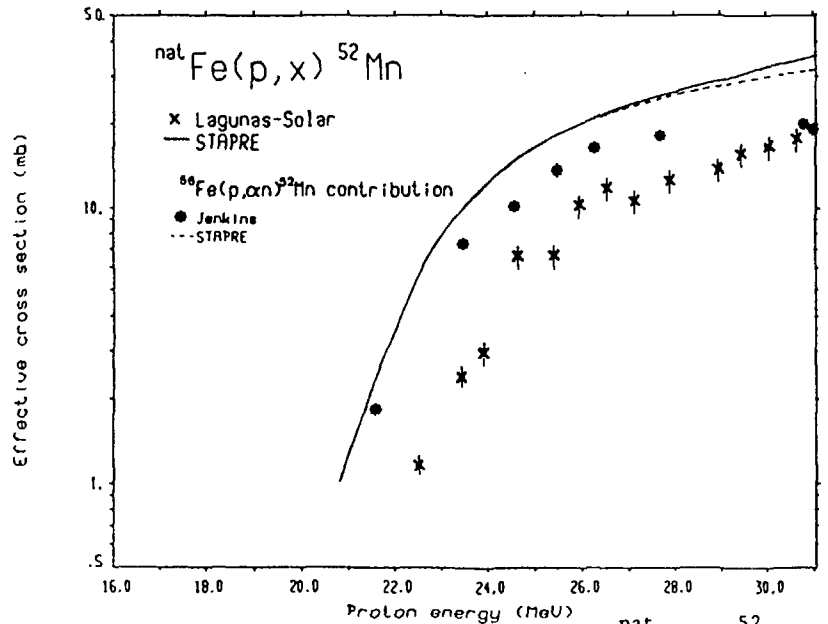

Figure 3 The calculated effective cross section for $^{nat}Fe(p,x)^{52}Mn$ compared with experimental results

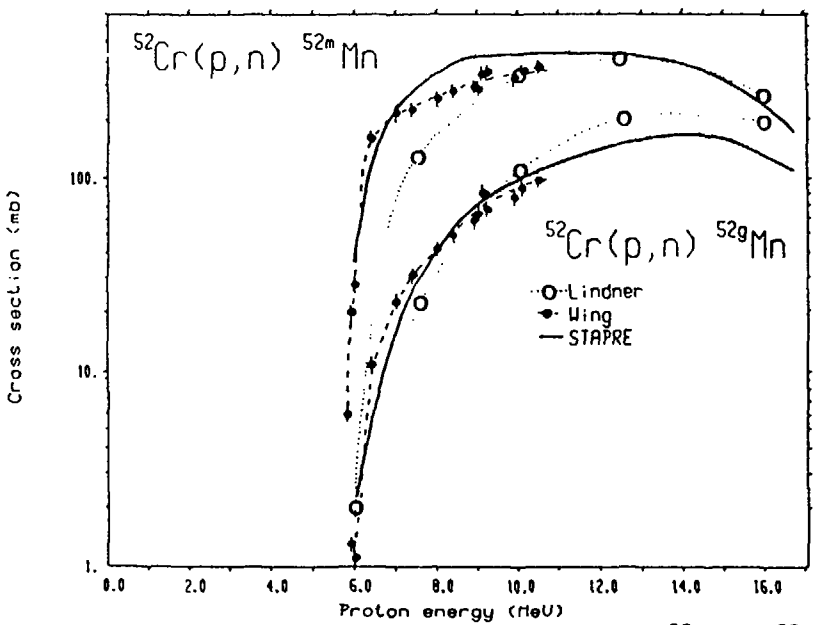

Figure 4 The calculated cross sections for the reactions $^{52}Cr(p,n)^{52g}Mn$ and $^{52}Cr(p,n)^{52m}Mn$ compared with experimental results

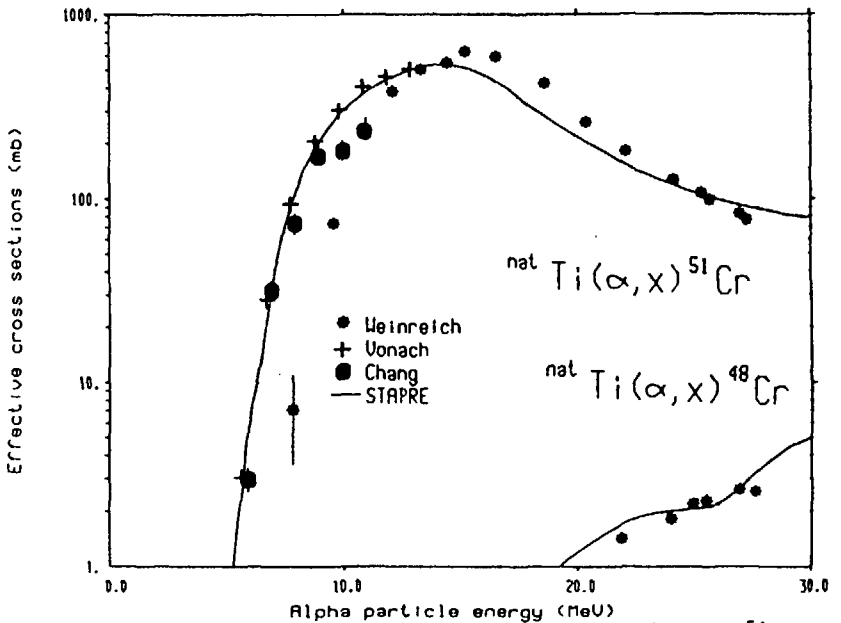

Figure 5 The calculated effective cross sections for $^{nat}Ti(\alpha,x)^{51}Cr$ and $^{nat}Ti(\alpha,x)^{48}Cr$ compared with experimental results

Conclusions

To obtain reliable and quite accurate results with nuclear reaction model codes a carefully selected model parameter set which should be adjusted to reproduce available experimental data in the mass region considered is necessary. Nuclear model codes are therefore useful to supplement and increase the nuclear data base for radioisotope production in connection with the evaluation of available experimental data. For proton and alpha-particle induced reactions on intermediate and heavier nuclei with incident particle energies up to 40 or 50 MeV calculated results with "uncertainties" of 30% seem possible, dependent on the experimental data base supporting the calculation.

True a-priori calculations with global parameter sets may be useful for a coarse estimate of an unknown excitation function. Under such conditions one may expect a reproduction of experimental results within a factor of about two.

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A computer code, OSCAR, for the calculation of excitation functions and reaction yields to produce radioisotope for medical purposes

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Abstract

For the purposes of predicting yields of radioisotopes produced by nuclear reactions with accelerated charged particles, a computer code, OSCAR, have been developed and utilized. The calculation is carried out in three steps; namely, computation of stopping powers for projectiles, estimation of excitation functions and computation of the yields of radioisotopes formed under the conditions of given nuclear reaction system. A computer routine has been developed to predict excitation functions for nuclear reactions with light ions($Z \leq 2$) using a systematics based on the nuclear masses, incident energy and Coulomb potential with inputting the atomic numbers and mass numbers of target nuclei, projectiles and product nuclei. In case of heavy-ion-induced reactions, a well known code, ALICE, is used to obtain excitation functions. Once excitation functions are made available either by calculation or measurements, the yields of all radioisotopes concerned with a given reaction system are estimated by use of the code OSCAR. Comparisons between calculated values and experimental results of the cross sections and the production yields for some medical radioisotopes are presented.

1. Introduction

Production and utilization of medical radioisotopes have grown remarkably over last twenty years so that the demands for nuclear data relevant to them, in particular of excitation functions, have been increased. Experimental data are often not available and calculation is needed to predict the excitation

functions and production yields. A computer code, OSCAR, has been developed to calculate the activity yield of a particular radioisotope(RI) produced by charged particle-induced reactions. To calculate the production yield of a RI, it is needed that stopping powers for projectiles in target matter and excitation functions of nuclear reactions concerned can be computed numerically. The code OSCAR involves routines for calculating the stopping powers, the excitation functions and production yields. The code is also utilized to know the mean projected range for energetic ions, that is useful for adjusting irradiation conditions of RI production with particle accelerators. In case the excitation function data are not available for given nuclear reactions in the routine, it is estimated using empirical formulas which have been developed in studying the mechanism of nuclear reactions[3,4]. The empirical formulas are effective in the light-ion reactions followed by successive neutron emissions.

The structure and functions of the code OSCAR are described in section 2. The calculation method of stopping power is given in section 3. Section 4 and 5 describe procedures for computing the excitation functions and the production yields, respectively. Comparisons between computed and experimental results are made on the excitation functions of some nuclear reactions and the thick-target yields of the reaction products.

2. Outline of the code OSCAR

The program was written in FORTRAN77 language. The executive file(load module) needs 230 KB in memory on a FACOM-380 computer. When the yield was computed including the preparation of excitation function by the empirical rule, typical CPU time was about 2 sec. Data files being linked to the code contains the data of all elements, such as atomic weight, density, excitation potential and so on. It is also containing nuclear mass excess[1] and excitation function data available in literature. Input data to calculate the thick-target yield are the reaction system, excitation function, half-life of the product, incident energy and bombarding time. The thickness of target matter is needed when the mean range of projectiles is longer than the thickness of the target. The calculation is executed in three stages as shown in Fig.1. The first stage is to calculate the stopping power for projectiles passing through the target matter. It is valid for particles of nuclear charges from 1 to 100 and for target of atomic numbers from 1 to 92 at the energy per nucleon from 1 keV/amu to 10 GeV/amu. The second stage is to estimate the excitation function for light-ion reaction followed by successive neutron emissions using our empirical rule that is described in section 4. In order to make the computation for other reaction types, we have tried to link with code ALICE offered by Blann[2] that is based on the statistical and pre-equilibrium theory. The last stage is the calculation of the production yield. The print output of OSCAR gives a list of input data followed by tables of the cross sections and production yields at various energy points.

3. Calculation of the stopping power

The stopping power is computed in a separate manner for each of three regions of projectile energy per nucleon, E/A. At high E/A region (100MeV/amu $\leqq$ E/A < 10 GeV/amu) where the particles can be considered to be completely ionized, Bethe's theory[3] is used. The stopping power S_T for ionization of a particle containing Z_1 protons, in a target of atomic number Z_2 and atomic weight A_2, is

$$S_T = -\frac{4\pi Z_1^2 e^4 N_A Z_2}{mv^2 A_2}\left[\ln\frac{2mv^2}{I(1-\beta^2)} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z_2}\right], \qquad (1)$$

where Z_1, Z_2 = Atomic numbers of projectile and target atom,
e, m = charge and mass of electron,
v = projectile velocity,
c = light velocity,
β = v/c,
N_A = Avogadro's number,
I = effective excitation potential in the target atom,
δ = density-effect correction, and
C = shell corrections.

At intermediate E/A region (0.2 MeV/amu ≦ E/A < 100 MeV/amu) where charge reduction is important and energy losses from elastic Coulomb collisions can not be ignored, an semi-empirical expression proposed by Ziegler[4] is applied. The total stopping power is

$$S_T = S_e + S_n \ , \qquad (2)$$

where S_e = electronic stopping power, and
S_n = nuclear stopping.

The expression for electronic part is described by assuming that the ion charge state is independent of the ion-target interaction. The ion-target stopping interaction could be empirically represented by proton stopping powers multiplied by the square of the ratio of the effective charge of the relevant ions to that of proton in the same material. That is

$$S_e = S_p \cdot (Z^*/Z_p^*)^2 \ , \qquad (3)$$

where Z^*, Z_p^* = effective charges of heavy ion and proton, and
S_p = electronic stopping power for proton.

The semi-empirical formulas for S_p and Z^*/Z_p^* are given by Andersen[5] and Ziegler[4]. Calculation of nuclear stopping is based on the LSS theory[6] which has been improved both from theoretical considerations and from an empirical approach[7]. This gives

$$S_n = 0.5 \ln(1 + \varepsilon)/(\varepsilon + 0.10718\varepsilon^{0.37544}) \ , \qquad (4)$$

where ε = reduced energy of projectile.

At low E/A region (1 keV/amu ≦ E/A < 200 keV/amu) where the nuclear stopping is more important than in the intermediate region, the electronic stopping is found to be proportional to the projectile velocity;

$$S_e = k\, E^{1/2} \ , \qquad (5)$$

where E = projectile energy, and
k = proportional constant.

The nuclear stopping in this region is also calculated by Eq.4.

Fig.2 shows the calculated results of the total, electronic and nuclear stopping powers as a function of the projectile energy per nucleon for ^{16}O in a gold target.

4. Calculation of the excitation functions

The empirical expression for calculating excitation functions consists of equations for the position E_{max} and height σ_{max} of the maxima and the form of the excitation function $\sigma(E)$, as follows;

$$E_{max} = \Delta Q + \Delta V_c + E_k \ , \qquad (6)$$

$$\sigma_{max} = \sigma_0 \cdot P_n \cdot (1 - P_f) \exp[\, -f(\Delta E_k) - f(\Delta V_c) - f(\Delta V_c') - f(\Delta M) \,], \qquad (7)$$

$$\sigma(E) = \sigma_{max} \cdot (E_{max}/E)^C \frac{\exp(C) - 1}{\exp(C \cdot E_{max}/E) - 1} \ , \qquad (8)$$

where Q = Q-value for the ground-to-ground transition,
V_c, V_c' = Coulomb barriers in entrance and exit channel,
E_k = kinetic energy of ejectile,
σ_0 = geometric cross section,
P_n, P_f = probabilities of neutron emission and fission,
M = nuclear mass, and
Δ = difference in the binding energy or Q-value.

The empirical formulas for E_{max} and σ_{max} are effective in (q,xn) and (q,r) type reactions where q stand for light projectile($Z \leqq 2$) and r stand for a light-charged ejectile. The expression for the form of the excitation function, however, is effective only in (q,xn) type reactions. Results of the excitation functions of some light-ion reactions followed by neutron emissions are compared with experimental results in Figs.3 - 7. In Fig.3 the

ratio of calculated to observed height of maxima of cross sections are plotted versus the mass number of compound nuclei. Most of the calculated maximum cross sections agree with experimental data within factor of 2. The comparison of the calculated excitation functions with available data for (p,xn) reactions in Fig.4, (d,xn) in Fig.5, (^{3}He,xn) in Fig.6 and (α,xn) in Fig.7 are shown, respectively. The measured and calculated excitation functions showed reasonable agreement. The position of maximum cross sections agreed with the experimental data within 2 MeV. The region where major discrepancies occur, was in the vicinity of the relevant threshould energy.

The values of E_{max} and σ_{max} for (q,xn) and (q,r) type reactions were calculated for the medical radioisotopes compiled by Gandarias-Cruz and Okamoto[33] as shown in Table 1. For the isotopes without measured data, only calculated results of E_{max} and σ_{max} are given.

5. Calculation of the production yields

The production yield is given by the following equation,

$$Y = N_t N_p (1 - e^{-\lambda t}) \int_{E_f}^{E_i} \{\sigma(E)/S(E)\} dE \ , \qquad (9)$$

where Y = yield,
N_t = number of target atoms,
N_p = number of projectiles,
λ = decay constant of the radionuclide,
t = bombarding time,
E_i, E_f = initial and final ion energies at the target,
σ = cross section of the nuclear reaction, and
S = stopping power for projectiles in the target matter.

Some calculated results by OSCAR are compared with experimental excitation functions and production yields in Fig.8 and 9. Fig.8 shows cross sections and production yields for (p,n) reactions on ^{67}Zn and ^{68}Zn as a function of the bombarding energy. The calculated excitation function can reproduced the experimental one except for high energies. Absolute values of the cross section at energies near the peak are in agreement with the experimental data within a factor of 2. The yields of ^{15}O and ^{11}C produced by the reaction system N + p are given in Fig.9. Such reactions that occur between light projectiles and light targets, have often many reasonance peaks in the excitation function. In such a case, OSCAR can not estimate the reaction cross section but can exactly compute the activity yields using the experimental excitation function.

6. Conclusion

A computer code, OSCAR, was written in FORTRAN77 language that computes production yields of radionuclides, stopping powers for projectiles and excitation functions for nuclear reactions. The method of calculation and the functions of the code were proved to work satisfactorily through the comparison between calculated and available experimental data. The code OSCAR would be an useful tool for medical radioisotope production.

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Table 1 Observed and calculated maximum cross sections, σ_{max}, and energy at the maximum cross section, E_{max}, for the medical radioisotopes compiled by Gandarias-Cruz and Okamoto[33]. The calculated values were obtained from the empirical rule on excitation functions.

Radio-isotope	Reaction	E_{max} [MeV] Obs.	Cal.	σ_{max} [mb] Obs.	Cal.
^{11}C	$^{11}B(p,n)$	3.69 - 10 (6)	15	62.3 - 338 (6)	250
	$^{14}N(p,\alpha)$	7.4 - 7.6 (3)	19	180 - 253 (3)	130
	$^{10}B(d,n)$	2.3 - 5.3 (3)	8	139 - 270 (3)	110
	$^{12}C(^3He,\alpha)$	2.7 - 8.9 (6)	14	165 - 350 (6)	83
^{13}N	$^{13}C(p,n)$	3.99 - 6.8 (11)	7	41.2 - 275 (11)	350
	$^{16}O(p,\alpha)$	7.99 - 14.7(7)	14	40 - 139 (7)	130
	$^{12}C(d,n)$	2.30 - 5.0 (6)	4	110 - 260 (6)	340
	$^{10}B(\alpha,n)$	2.98, 4.69 (2)	3	27.3, 106 (2)	320
^{15}O	$^{15}N(p,n)$	6.45 - 6.6 (3)	15	182 - 230 (3)	290
	$^{14}N(d,n)$	2.7 - 4.3 (4)	7	25 - 300 (4)	180
	$^{16}O(^3He,\alpha)$	6.6 (1)	13	169 (1)	75
	$^{12}C(\alpha,n)$	14.5 - 22.4(6)	20	9.2 - 22.8 (6)	200
^{18}F	$^{18}O(p,n)$	2.64 - 7 (7)	11	40 - 630 (7)	340
	$^{19}F(d,t)$	$\geqq$15.2 (1)	16	290 (1)	380
	$^{20}Ne(d,\alpha)$	<24.69 (1)	11	11.6 (1)	100
	$^{16}O(^3He,p)$	4.5 - 13.9 (3)	10	135.9 -436 (3)	260
	$^{16}O(^3He,n)$		10		270
^{22}Na	$^{24}Mg(d,\alpha)$	8.7 (1)	14	190 (1)	85
	$^{19}F(\alpha,n)$	8 (1)	12	280 (1)	270

Radio-isotope	Reaction	E_{max} [MeV] Obs.		Cal.	σ_{max} [mb] Obs.		Cal.
^{30}P	$^{32}S(d,\alpha)$	10	(1)	12	40	(1)	71
	$^{28}Si(^{3}He,p)$	16	(1)	10	68	(1)	270
	$^{27}Al(\alpha,n)$	8.8 - 15.8	(3)	12	350 - 480	(3)	320
	$^{28}Si(\alpha,d)$	25.5 - 34.4	(2)	25	70 - 150	(2)	260
^{34m}Cl	$^{32}S(^{3}He,p)$	8	(1)	10	37	(1)	<270
	$^{31}P(\alpha,n)$	>7	(1)	14	28	(1)	<330
^{38}K	$^{40}Ar(p,3n)$			41			120
	$^{40}Ca(d,\alpha)$	>5.5	(1)	14	4.77	(1)	57
	$^{37}Cl(^{3}He,2n)$	14.7 - 15	(1)	17	23	(1)	370
	$^{35}Cl(\alpha,n)$			14			350
	$^{37}Cl(\alpha,3n)$			42			97
^{43}K	$^{40}Ar(\alpha,p)$	18	(1)	20	68	(1)	270
^{44}Ti	$^{45}Sc(p,2n)$	32	(1)	28	65	(1)	87
	$^{45}Sc(d,3n)$			35			25
	$^{44}Ca(^{3}He,3n)$			34			24
^{45}Ti	$^{45}Sc(p,n)$	5-10, >14.4	(4)	15	188 - 450	(4)	500
	$^{45}Sc(d,2n)$			21			310
	$^{44}Ca(^{3}He,2n)$			19			300
^{48}Cr	$^{51}V(d,5n)$	70	(1)	68	0.95	(1)	2.8
^{51}Cr	$^{51}V(p,n)$	10 - 11.3	(5)	13	540 - 834	(5)	550
	$^{51}V(d,2n)$	17	(1)	19	678	(1)	460
^{51}Mn	$^{52}Cr(p,2n)$			27	120	(1)	480
	$^{50}Cr(d,n)$			7			190
	$^{51}V(^{3}He,3n)$			29			420

Radio-isotope	Reaction	E_{max} [MeV] Obs.		Cal.	σ_{max} [mb] Obs.		Cal.
^{52g}Mn	$^{52}Cr(p,n)$	10.5 - 12.5	(2)	15	98 - 203	(2)	<540
^{52m}Mn	$^{52}Cr(p,n)$	10.5 - 12.5	(2)	15	370 - 410	(2)	<540
^{52}Mn	$^{52}Cr(d,2n)$	15 - 18.5	(2)	21	150 - 200	(2)	460
	$^{51}V(^{3}He,2n)$			16			350
^{52}Fe	$^{55}Mn(p,4n)$			58			4.5
	$^{52}Cr(^{3}He,3n)$	34	(1)	35	5	(1)	15
	$^{50}Cr(\alpha,2n)$	28	(1)	30	1	(1)	4.3
^{55}Co	$^{56}Fe(p,2n)$	23.5, 25	(2)	27	65, 67	(2)	500
	$^{54}Fe(d,n)$	7 - 8	(4)	7	50 - 260	(4)	190
	$^{55}Mn(^{3}He,3n)$	28	(1)	28	25	(1)	27
	$^{55}Mn(\alpha,4n)$	57.77	(1)	54	11.6	(1)	100
^{57}Co	$^{60}Ni(p,\alpha)$	13.2 - 50.8	(2)	20	40 - 191	(2)	54
^{56}Ni	$^{56}Fe(^{3}He,3n)$	>29.3	(1)	34	2.1	(1)	7
	$^{54}Fe(\alpha,2n)$	30 - 32.5	(3)	30	4 - 11.7	(3)	25
^{57}Ni	$^{56}Fe(^{3}He,2n)$	18	(1)	20	48	(1)	190
^{61}Cu	$^{60}Ni(d,n)$			7			190
	$^{59}Co(\alpha,2n)$	<26	(1)	24	457	(1)	450
	$^{58}Ni(\alpha,p)$	11 - 17	(3)	18	316 - 770	(3)	260
^{62}Cu	$^{62}Ni(p,n)$	6.66 - 11.6	(2)	14	430 - 480	(2)	600
	$^{59}Co(\alpha,n)$	11 - 15	(2)	14	363 - 676	(2)	480

Radio-isotope	Reaction	E_{max} [MeV] Obs.		Cal.	σ_{max} [mb] Obs.		Cal.
^{62}Zn	^{63}Cu(p,2n)	24 - 27	(5)	26	64 - 218	(5)	540
	^{63}Cu(d,3n)	33	(1)	32	73	(1)	450
	^{60}Ni(^{3}He,n)			10			17
	^{61}Ni(^{3}He,2n)			17			360
	^{62}Ni(^{3}He,3n)			31			430
	^{60}Ni(α,2n)	31 - 33	(4)		120 - 230	(4)	450
^{67}Ga	^{67}Zn(p,n)	>5.34,>6.37	(2)	10	130, 420	(2)	670
	^{68}Zn(p,2n)	20	(1)	23	430	(1)	580
	^{66}Zn(d,n)	8, 8.8	(2)	7	221, 450	(2)	150
	^{65}Cu(^{3}He,n)	11.8, 12	(2)	7	7.68, 13	(2)	5
	^{65}Cu(α,2n)	26.5 - 28.5	(4)	25	520 - 967	(4)	480
	^{64}Zn(α,p)	18 - 20	(2)	19	452 - 515	(2)	270
^{68}Ge	^{69}Ga(p,2n)	22	(1)	24	490	(1)	570
	^{71}Ga(p,4n)	42.4	(1)	49	134	(1)	530
	^{69}Ga(d,3n)			30			510
	^{66}Zn(^{3}He,n)			11			8.0
	^{67}Zn(^{3}He,2n)			17			130
	^{68}Zn(^{3}He,3n)			29			493
	^{66}Zn(α,2n)			29			470
	^{68}Zn(α,4n)			53			460
^{74}As	^{71}Ga(α,n)			15			420
^{72}Se	^{75}As(p,4n)	50	(1)	50	120	(1)	20
	^{70}Ge(α,2n)	34.1, 34	(2)	29	324, 1610	(2)	260

Radio-isotope	Reaction	E_{max} [MeV] Obs.		Cal.	σ_{max} [mb] Obs.		Cal.
^{73}Se	^{75}As(p,3n)	35	(1)	38	350	(1)	82
	^{75}As(d,4n)	41.2	(1)	44	77	(1)	70
	^{72}Ge(^{3}He,2n)	22.5	(1)	19	309	(1)	420
	^{73}Ge(^{3}He,3n)	>36.5	(1)	28	1498	(1)	74
	^{70}Ge(α,n)	23.5	(1)	18	504	(1)	510
	^{72}Ge(α,3n)	>39.5	(1)	42	435	(1)	70
^{75}Br	^{76}Se(p,2n)	21.4	(1)	24	520	(1)	380
	^{74}Se(d,n)			6.7			190
	^{76}Se(d,3n)	30.7	(1)	30	370	(1)	150
	^{75}As(^{3}He,3n)	25 - 31	(3)	26	186 - 352	(3)	150
	^{75}As(α,4n)	53.8, 55	(2)	50	186, 268	(2)	22
^{76}Br	^{75}As(^{3}He,2n)	15.3 - 20	(3)	16	141 - 216	(3)	210
	^{75}As(α,3n)	34 - 38	(3)	38	154 - 430	(3)	170
^{77}Br	^{77}Se(p,n)	>5.54, >9.9	(2)	10	232, 328	(2)	710
	^{78}Se(p,2n)	22	(1)	23	800	(1)	620
	^{75}As(α,2n)	25 - 26.3	(3)	24	690 - 950	(3)	520
^{77}Kr	^{79}Br(p,3n)	35 - 36	(3)	39	150 - 260	(3)	3
	^{81}Br(p,5n)	60	(1)	65	41	(1)	0.25
	^{76}Se(^{3}He,2n)	22	(1)	20	370	(1)	72
	^{77}Se(^{3}He,3n)	31	(1)	30	356	(1)	2.9
^{79}Kr	^{79}Br(p,n)	<10, 10.98	(2)	12	690, 724	(2)	700
	^{81}Br(p,3n)	30	(1)	36	480	(1)	170
^{81}Rb	^{80}Kr(d,n)			7			130
	^{79}Br(α,2n)	30	(1)	24	380	(1)	540
	^{85}Rb(p,5n)	68, 68	(2)	68	28	(1)	0.21

Radio-isotope	Reaction	E_{max} [MeV] Obs.		Cal.	σ_{max} [mb] Obs.		Cal.
^{82}Sr	$^{85}Rb(p,4n)$	50	(1)	52	230	(1)	34
	$^{82}Kr(^{3}He,3n)$			31			150
^{87}Y	$^{87}Sr(p,n)$	>6.8	(1)	12	324	(1)	740
	$^{88}Sr(p,2n)$	25	(1)	25	1210	(1)	660
	$^{86}Sr(d,n)$			8			85
^{87m}Y	$^{87}Rb(^{3}He,3n)$	25	(1)	25	30	(1)	<580
	$^{85}Rb(\alpha,2n)$	25, 29	(2)	24	450, 700	(2)	<560
^{94}Ru	$^{92}Mo(\alpha,2n)$	30	(1)	30	397	(1)	580
^{95}Ru	$^{92}Mo(\alpha,n)$	19.1, 20	(2)	19	370, 574	(2)	600
^{97}Ru	$^{94}Mo(\alpha,n)$	18	(1)	18	702	(1)	440
	$^{95}Mo(\alpha,2n)$	28	(1)	27	1293	(1)	590
^{101m}Rh	$^{101}Ru(p,n)$	>6.19	(1)	11	132	(1)	<420
^{101}Pd	$^{103}Rh(p,3n)$	32	(1)	35			690
^{109}Cd	$^{109}Ag(d,2n)$	13.3	(1)	14	930	(1)	730
^{111}In	$^{111}Cd(p,n)$	6.4 - 13.1	(5)	11	200 - 696	(5)	400
	$^{112}Cd(p,2n)$	20.9 - 22.8	(2)	22	1000 - 1070	(2)	770
	$^{109}Ag(^{3}He,n)$	19, 20	(2)	10	2.2, 4	(2)	0.83
	$^{109}Ag(\alpha,2n)$	26, 30.3	(2)	25	872, 1200	(2)	650
^{113}Sn	$^{113}In(p,n)$			12			400
	$^{115}In(p,3n)$			32			740
	$^{113}In(d,2n)$			15			740
	$^{112}Cd(^{3}He,2n)$			18			39
	$^{113}Cd(^{3}He,3n)$			25			530
	$^{111}Cd(\alpha,2n)$			26			660
^{118}Te	$^{121}Sb(p,4n)$	44	(1)	44			740
	$^{123}Sb(p,6n)$			67			720
	$^{117}Sn(^{3}He,2n)$			19			39
	$^{118}Sn(^{3}He,3n)$			28			690
	$^{116}Sn(\alpha,2n)$	>29.7	(1)	29	1500	(1)	670
^{122}Xe	$^{127}I(p,6n)$	67.5 - 70	(2)	69	114 - 197	(2)	720
	$^{127}I(d,7n)$	85	(1)	76	190	(1)	430
	$^{122}Te(^{3}He,3n)$			29			700
^{123}I	$^{123}Te(p,n)$			11	210	(1)	400
	$^{124}Te(p,2n)$	24.6	(1)	22	1300	(1)	820
	$^{122}Te(d,n)$	11.05	(1)	9	351	(1)	67
	$^{121}Sb(\alpha,2n)$	26.5 - 27.6	(2)	25	816 - 1110	(2)	690
^{123}Xe	$^{127}I(p,5n)$	53.5 - 57.5	(4)	57	269 - 484	(4)	740
	$^{127}I(d,6n)$	70	(1)	63	290	(1)	700
	$^{123}Te(^{3}He,3n)$	26	(1)	27	178	(1)	710
	$^{124}Te(^{3}He,4n)$	45	(1)	39	162	(1)	700
	$^{122}Te(\alpha,3n)$			41			680
^{125}Xe	$^{127}I(p,3n)$	29.6, 30	(2)	32	648, 820	(2)	790
	$^{127}I(d,4n)$	47.4	(1)	37	460	(1)	730
^{127}Cs	$^{127}I(\alpha,4n)$	53.5	(1)	47	2180	(1)	690

Radio-isotope	Reaction	E_{max} [MeV] Obs.		Cal.	σ_{max} [mb] Obs.		Cal.
^{128}Ba	^{133}Cs(p,6n)	65	(1)	68	290	(1)	750
	^{133}Cs(d,7n)			75			490
	^{128}Xe(^{3}He,3n)			28			730
^{129}Cs	^{127}I(α,2n)	25	(1)	25	1900	(1)	710
^{129}Ba	^{133}Cs(p,5n)	57	(1)	56	468	(1)	770
^{131}Ba	^{133}Cs(p,3n)			32			810
^{167}Tm	^{167}Er(p,n)			12			170
	^{166}Er(d,n)			10			36
	^{165}Ho(α,2n)	23.1, 28	(2)	26	730, 825	(2)	840
^{178}W	^{181}Ta(p,4n)	36.3	(1)	39	772	(1)	950
	^{177}Hf(^{3}He,2n)			21			5.3
	^{178}Hf(^{3}He,3n)			28			110
	^{176}Hf(α,2n)			29			870
^{195m}Hg	^{197}Au(p,3n)	27	(1)	29			<1030
	^{197}Au(d,4n)	36.1	(1)	34	614	(1)	<960
	^{194}Pt(^{3}He,2n)			21			<5.4
	^{192}Pt(α,n)			22			<68
^{201}Tl	^{202}Hg(p,2n)			20			1100
^{201}Pb	^{203}Tl(p,3n)	27.4	(1)	30	1250	(1)	1100
	^{205}Tl(p,5n)	45.7, 45.7	(2)	51	880,1020	(2)	1000

Radio-isotope	Reaction	E_{max} [MeV] Obs.		Cal.	σ_{max} [mb] Obs.		Cal.
^{203}Pb	^{203}Tl(p,n)			13			110
	^{205}Tl(p,3n)	27.3	(1)	29	1310	(1)	1100
	^{204}Pb(d,3n)	24-25	(1)	25	730	(1)	1000
	^{203}Tl(^{3}He,3n)			27			1300
^{211}At	^{209}Bi(α,2n)	31	(1)	29	980	(1)	970

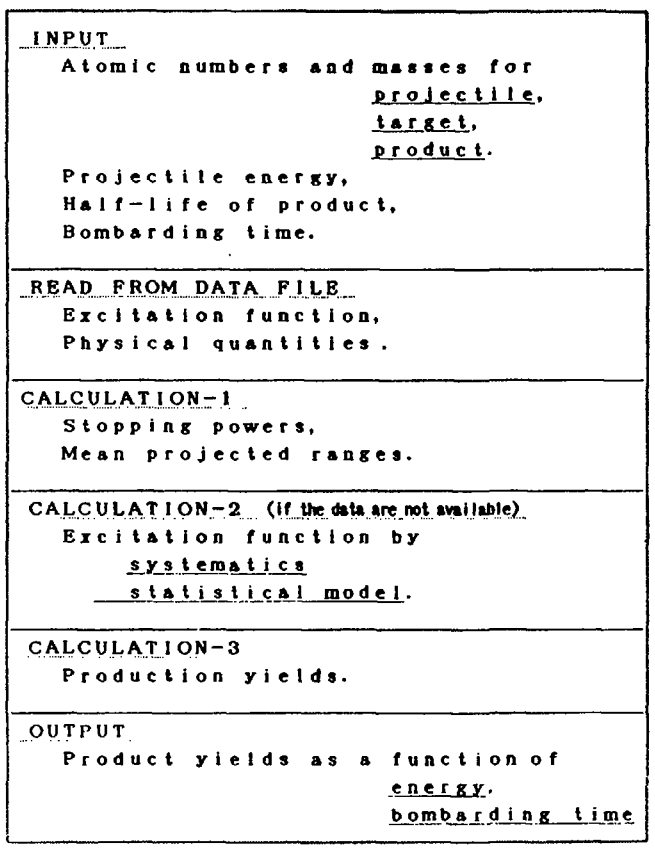

Fig. 1 Structure of the computer code, OSCAR

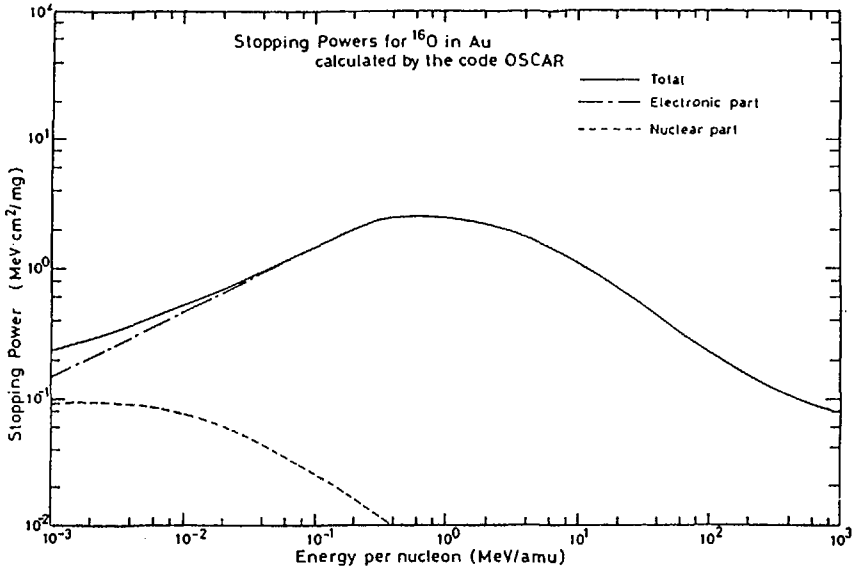

Fig.2 Representative calculation of stopping powers for ^{16}O in Au at incident energies per nucleon from 1 keV/amu to 1 GeV/amu.

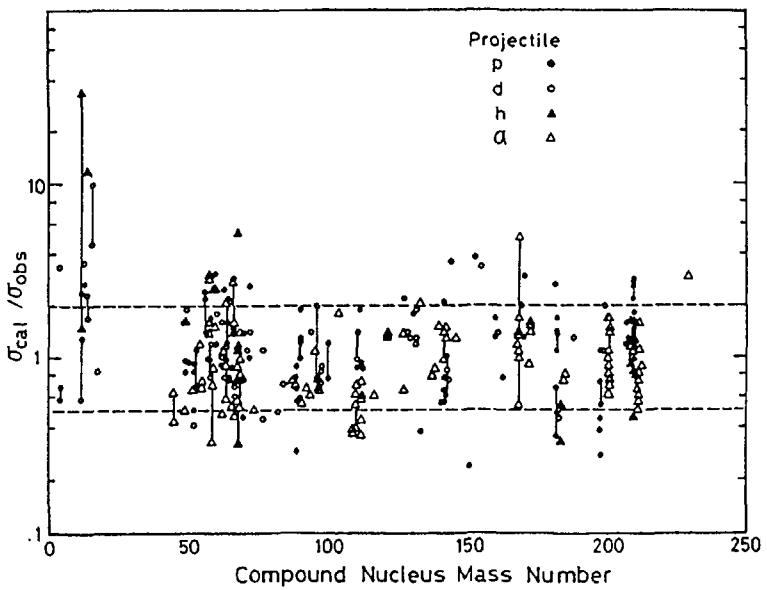

Fig.3 Ratios of experimental and calculated cross sections at peak of the excitation functions for light-ion reactions. The calculated values were obtained from the empirical rule on excitation functions.

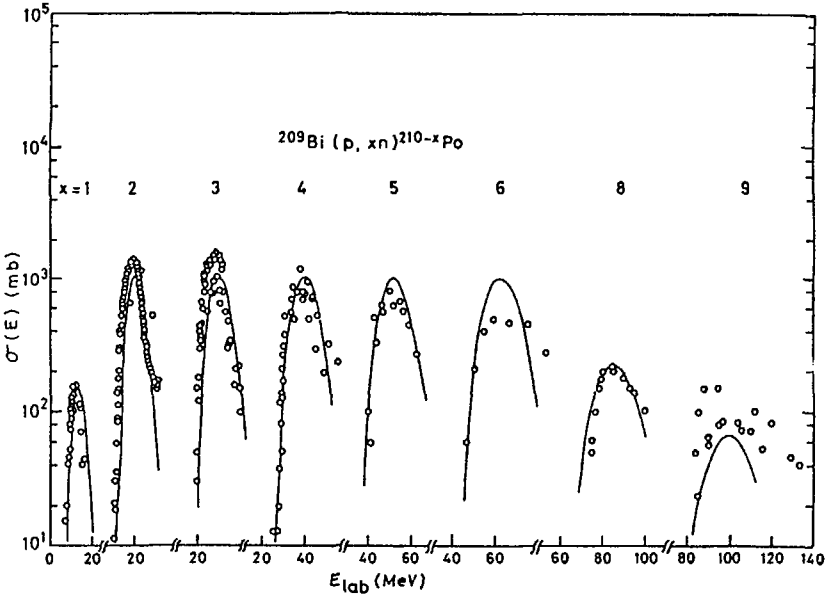

Fig.4 Comparison between experimental and calculated excitation functions for $^{209}Bi(p,xn)$ reactions. Data points and solid lines represent experimental and calculated values, respectively. (Ref. 8, 9, 10, 15, 17, 19, 25, 29)

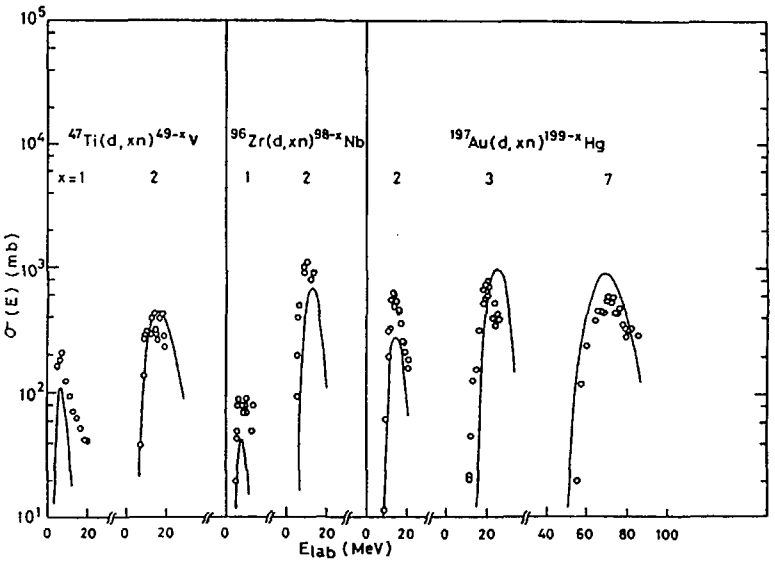

Fig.5 Comparison between experimental and calculated excitation functions for (d,xn) reactions on ^{47}Ti, ^{96}Zr and ^{197}Au targets. The meaning of the symbols is the same as those in Fig.4. (Ref.11, 12, 16, 20, 22, 27)

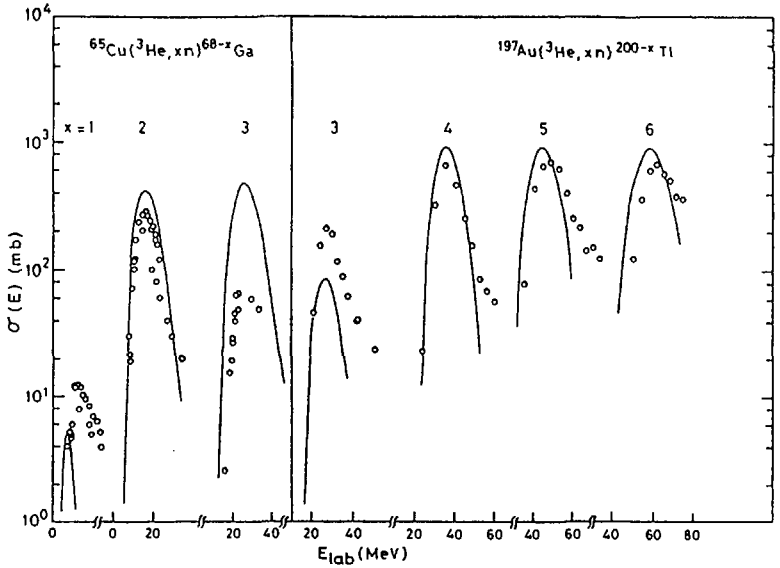

Fig.6 Comparison between experimental and calculated excitation functions for (^{3}He,xn) reactions on ^{65}Cu and ^{197}Au targets. The meaning of the symbols is the same as those in Fig.4. (Ref.13, 23, 28)

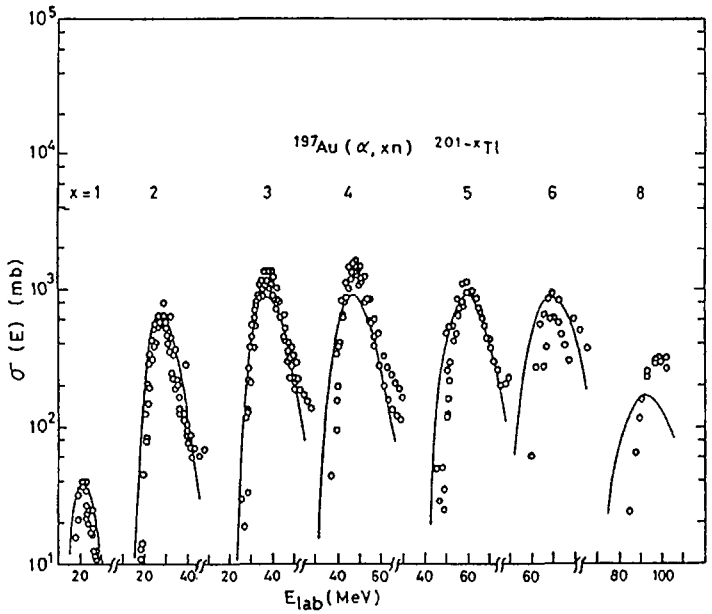

Fig.7 Comparison between experimental and calculated excitation functions for ^{197}Au(α,xn) reactions. The meaning of the symbols is the same as those in Fig.4. (Ref.14, 18, 24, 26)

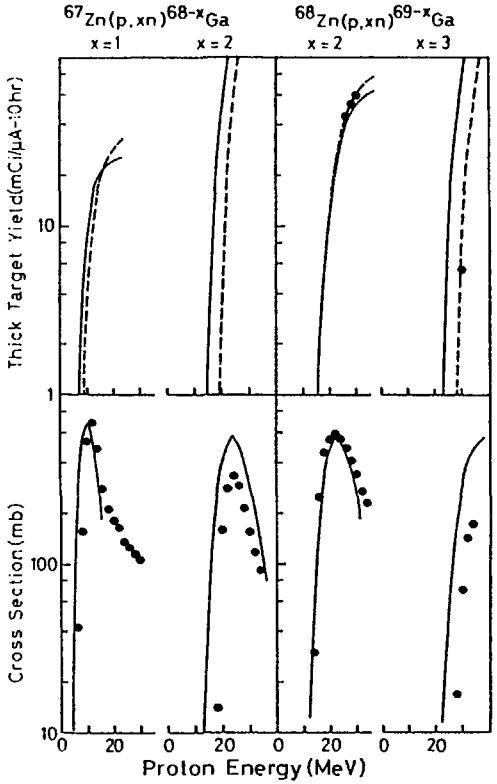

Fig.8 Comparison between experimental and calculated values of cross sections and thick-target yields for ^{67,68}Zn(p,xn) reactions. Data points and solid lines represent experimental[31] and calculated values, respectively. Dotted lines correspond to the yields calculated using the experimental excitation functions[31].

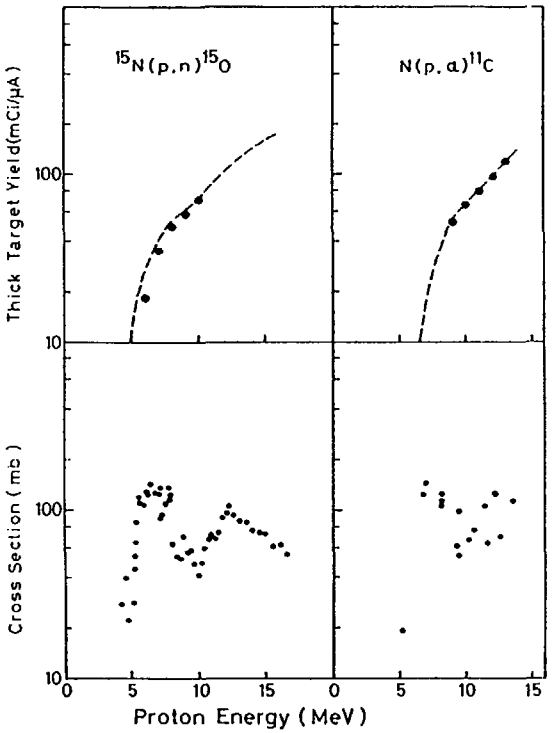

Fig.9 Thick-target yield curves for the reactions $^{15}N(p,n)^{15}O$ and $^{14}N(p,\alpha)^{11}C$ calculated using experimental excitation functions[30,32] are compared with experimental ones[30,32]. The meaning of symbols is the same as those in Fig.8.

SESSION IV

COMPILATION AND EVALUATION

NUCLEAR DATA FOR MEDICAL RADIOISOTOPES PRODUCED BY ACCELERATORS - STATUS AND COMPILATION

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ABSTRACT

The status of data on excitation functions and thick target yields for medical radioisotopes produced by accelerators is summarized.

The nuclear decay mode, production method, Q-value, maximum production cross-section and its energy at maximum cross-section value are tabulated for the medical radioisotopes in use.

Explanation of the table and appendices

The selection of isotopes and reactions is based on the contributed paper by the Nuclear Data Section presented at the IAEA Advisory Group Meeting on Nuclear and Atomic Data for Radiotherapy and related Radiobiology, Rijswijk, the Netherlands, 16-20 September 1985 (to be published in August 1987 as an IAEA Panel Proceedings Series STI/PUB/741) and from other references [253, 254].

The half-life and decay mode values are taken from ref. [255]. The Q-value is taken from [256, 257]. The maximum cross-section value (σ max), the energy at maximum cross-section value (E(σ max)) and the energy range of experimental measurements are taken from the EXFOR library, the original publications and in some cases from ref. [258].

In the table some reactions are listed without cross-section data. This means that no nuclear data are given in these reactions which are useful or potentially useful for medical radioisotope production.

Appendix I and II explain in detail the status of cross section (SIG) and thick-target yield (TTY) data respectively, compiled in EXFOR up to January 1987. The nuclear reaction in both appendices appear in the same order as in the table.

Note: The result of a recent survey on several additional data is included, following the discussions during the IAEA Consultants' Meeting on "Data Requirements for Medical Radioisotope Production", Tokyo, 20-24 April 1987.

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
6-C-11	20.39±0.02 min	β^+(99.8).EC(0.2)	$^{10}B(p,\gamma)^{11}C$	8.6913	1.2	0.0075	0.6-2.6	1,3
					4	0.0099	2.6-17	2
					7	0.0111		
					8.7	0.0114		
			$^{11}B(p,n)^{11}C$	-2.7647	10	100	2.5-400	4
					9.3	100	0.2-98.6	5
					8.5	332	4.7-15	6
					9.8	338		
					3.69	62.3	2.9-5.5	7
					>5.5	102		
					<40	31	40-155	8
					<36.5	22.9	36.5-152	9
			$^{12}C(p,np)^{11}C$	-18.7219	46	100	8.5-104	5
					33	92	20.7-50.5	11
					34	89	27.6-41.8	12
					>32	89	15.9-32	10
					<93	70.5	93-340	
					<50	86.4	50-28000	13,14,15,16,8
			$^{14}N(p,\alpha)^{11}C$	-2.9221	7.4	180	4-14	17
					7.6	253	5-22	18
					7.4	243	4.65-14.72	19
			$^{10}B(d,n)^{11}C$	6.4667	5.3	175	1.5-12	20
					2.3	270	0.5-3.2	21
					<2.93	139	2.93-11	22
			$^{12}C(^3He,\alpha)^{11}C$	1.8566	8.9	340	4.5-24	23
					8.9	350	2.4-9.5	24
					2.7	165	1.56-5.78	25
					4.3	255		
					4.85	281		
					5.6	293		
7-N-13	9.965±0.004 min	β^+(99.8),EC(0.2)	$^{12}C(p,\gamma)^{13}N$	1.9435	>0.45	0.065	0.085-0.45	26,27,28
						2.5,1.8	5,11	29
			$^{13}C(p,n)^{13}N$	-3.003	6.8	200	3.2-6.8	4
					3.9925	130	3.24-4.25	30
					4.150	62.5		
					3.990	83.0	3.88-5.27	7
					4.140	41.2		
					4.520	79.0		
					5.030	94.0		
					4.0	120	3.2-12.9	34
					5.05	170		
					6.7	275		
					6.7	230	5-13.5	35
						1.9	155	8
			$^{16}O(p,\alpha)^{13}N$	-5.2182	8.5	40	6.22-15.6	12
					11.4	50		
					14.6	40		
					10.9	79	9.7-15	6
					12.5	41		
					14.7	50		
					7.99	139	6.7-9.27	31
					>7.71	13.8	6.51-7.71	32
			$^{12}C(d,n)^{13}N$	-0.2812	5.0	110	2-20	33
					5.0	120	2-18	20
					>3.0	260	0.4-3	36
					2.30	200	1.96-4.5	37
					3.98	153		
					>4.5	162		
			$^{10}B(\alpha,n)^{13}N$	1.0598	2.98	27.3	2.55-4.83	7
					4.69	106		
8-O-15	2.037±0.003 min	β^+(99.9),EC(0.1)	$^{15}N(p,n)^{15}O$	-3.5417	6.6	230	5.5-13.5	35
					6.5	190	3.95-9	38
					6.45	182	5.8-8.6	39
			$^{14}N(d,n)^{15}O$	5.0673	3.68	28	2-5	40
					2.7	25	0.9-5.3	41
					4.3	210	0.6-14.35	42
					>3.2	300	0.5-3.2	21
			$^{16}O(^3He,\alpha)^{15}O$	4.9090	6.6	169	2.9-8.9	24
			$^{12}C(\alpha,n)^{15}O$	-8.5078	15.5	9.4	15-19	43
					16.6	9.2		
					17.3	10.5		
					18.5	9.7		
					14.5	26	11.4-22.7	44
					22.4	22.8		

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
9-F-18	1.8295±0.0008h	β^+(96.9),EC(3.1)	$^{18}O(p,n)^{18}F$	-2.4378	7	40	6-13	45
					2.64	140	2.5-3.9	46
					3.02	220		
					3.37	190		
					3.86	280		
					5.2	630	2.3-14.7	47
					<7	95	7-13.5	48
			$^{19}F(d,t)^{18}F$	-4.1731	≥15.2	290	5.8-15.2	49
			$^{20}Ne(d,\alpha)^{18}F$	2.7968	<24.69	11.6	24.7-76	50
			$^{16}O(t,n)^{18}F$	1.2692	>2.1	100	0.68-2.13	51
					>3	820	0.5-3	52
			$^{16}O(^3He,p)^{18}F$	2.0330	6.3	436	2.9-9.5	24
					>4.5	139	1.5-4.5	53
					<13.9	135.9	13.9-40.3	54
			$^{16}O(\alpha,pn)^{18}F$	-18.5455	≥40	250	21-40	55
			daughter of ^{18}Ne					
			$^{18}Ne \xrightarrow[(1.672s)]{\beta+} {}^{18}F$					
			$^{20}Ne(d,p3n)^{18}Ne$	-30.73	57.5	23	40-76.0	50
			$^{16}O(^3He,n)^{18}Ne$	-3.196				
			$^{20}Ne(^3He,\alpha n)^{18}Ne$	-15.517	30.9	2.7	18.44-30.9	50
11-Na-22	2.602±0.002 a	β^+(89.4),EC(10.6)	$^{24}Mg(d,\alpha)^{22}Na$	1.9629	8.7	190	0.9-16.1	56
			$^{19}F(\alpha,n)^{22}Na$	-1.9500	8	280	2.4-8.0	57
12-Mg-28	20.90±0.03 h	β^-(100)	$^{30}Si(\gamma,2P)^{28}Mg$	-23.9927		Yield	30-60	58
			$^{30}Si(p,3p)^{28}Mg$	-23.9927	(400)	2.8	130-425	59
			$^{31}P(p,4p)^{28}Mg$	-31.290	(300)	0.328	130-425	59
			$^{32}S(p,5p)^{28}Mg$	-34.095		0.005	130	59
						0.004	400	
			$^{26}Mg(t,p)^{28}Mg$	6.4648	5.4	6.8	2-20	60
					7	8	2-20	61
			$^{27}Al(t,2p)^{28}Mg$	-1.806	22	4.5	5-23	61
			$^{26}Mg(\alpha,2p)^{28}Mg$	-13.350	42.8	2.92	17.2-152	62
					33-34	1.67	18.9-36.6	63
			$^{27}Al(\alpha,3p)^{28}Mg$	-21.6207	55	0.46	30-160	62
					60	0.65	35.7-102.3	64
					>42	0.1	31-42	63
			$S(p,x)^{28}Mg$		130	0.036	50-180	65
					(300)	0.009	130-425	59
			$Si,P,Cl,Ar,K(p,x)^{28}Mg$		>120		50-180	65
15-P-30	2.498±0.004 min	β^+(99.9),EC(0.1)	$^{31}P(p,pn)^{30}P$	-12.3073	26	260	19.6-34.4	66
			$^{32}S(d,\alpha)^{30}P$	4.901	10	40	4-14	68
			$^{28}Si(^3He,p)^{30}P$	6.3553	16	68	12-36	68
			$^{27}Al(\alpha,n)^{30}P$	-2.6378	9.8	350	5.2-11.0	69
					15	400	10-27	66
					8.8-15.8	480	0-34.4	70
			$^{28}Si(\alpha,d)^{30}P$	-11.9985	25.5-34.4	150	0-34.4	70
					>26	70	16-26	68
16-S-38	2.84±0.01 h	β^-(100)	$^{40}Ar(\gamma,2p)^{38}S$	-22.755		Yield	60-85	71,72
			$^{40}Ar(p,3p)^{38}S$	-22.755	>49	0.10	33-49	73
17-Cl-34m	32.23±0.14 min	β^+(54),IT(44.5), EC(1,5)	$^{35}Cl(p,pn)^{34m}Cl$	-12.6463			10-45	74
						120	21.5	67
			$^{32}S(^3He,p)^{34m}Cl$	6.0666	8	37	3.8-22.1	75
			$^{31}P(\alpha,n)^{34m}Cl$	-5.6479	>7	28	6.5-7	76

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
19-K-38	7.636±0.018 min	β^+(99.5),EC(0.5)	$^{40}Ca(\gamma,pn)^{38}K$	-21.4146		Yield	30-60	77
			$^{40}Ar(p,3n)^{38}K$	-23.1736		Yield	30-32	78
			$^{40}Ca(d,\alpha)^{38}K$	4.657	>5.5	4.77	1.9-5.5	79
			$^{37}Cl(^3He,2n)^{38}K$	-4.182	14.7-15	23	7.3-20.2	75
			$^{40}Ca(^3He,\alpha p)^{38}K$	0.837	>20.2	76.6	8.1-20.2	75
			$^{35}Cl(\alpha,n)^{38}K$	-5.868		Yield	4-30	80,81
			$^{37}Cl(\alpha,3n)^{38}K$	-24.760				
19-K-43	22.3±0.1 h	β^-(100)	$^{40}Ar(\alpha,p)^{43}K$	-3.322	18	68	11.6-36.7	82
			V(p,spall)^{43}K			3.8,5.4	590,800	83
20-Ca-47	4.536±0.002 d	β^-(100)	$^{48}Ca(p,pn)^{47}Ca$	-9.951	<120	118	120-660	259
			$^{48}Ca(^3He,\alpha)^{47}Ca$	10.627	>43	82	5-43	260
			$^{48}Ca(\alpha,\alpha n)^{47}Ca$	-9.951	34-37	127	19.3-39	261,260
			$^{51}V(\alpha,5p3n)^{47}Ca$	-68.09	>171	0.378	81.8-171	132
			$^{238}U(p,x)^{47}Ca$			1.59	300000	262
21-Sc-47	3.341±0.03 d	β^-(100)	$^{48}Ti(\gamma,p)^{47}Sc$	-11.4459		Yield	30-60	84
			$^{51}V(\gamma,\alpha)^{47}Sc$	-10.2934		Yield	30-60	84
			Ni(p,spall)^{47}Sc			1.49	800	83
22-Ti-44	47.3±1.2 a	EC(100)	$^{45}Sc(p,2n)^{44}Ti$	-12.369	32	65	15-85	85
GENERATOR			$^{45}Sc(d,3n)^{44}Ti$	-14.594				
21-Sc-44	3.927±0.008 h	β^+(94),EC(6)	$^{44}Ca(^3He,3n)^{44}Ti$	-13.199				
			Ti(α,2pxn)^{44}Ti		>171	3.3	43-171	86
			$^{51}V(p,spall)^{44}Ti$	-70.4		Yield	200	87
22-Ti-45	3.080±0.008 h	β^+(85),EC(15)	$^{45}Sc(p,n)^{45}Ti$	-2.8449	>14.4	394	7.8-14.4	88,90
					<10	450	10-85	85
					>5	230	2.9-5.3	89
					>6.77	188	3.28-6.77	91
						350	12.0	92
						179	6.75	93
					<120	3.8	120-670	94
			$^{45}Sc(d,2n)^{45}Ti$	-5.0696				
			$^{44}C(^3He,2n)^{45}Ti$	-3.674				
24-Cr-48	21.56±0.03 h	EC(98.53), β^+(1.47)	$^{51}V(d,5n)^{48}Cr$	-36.6034	70	0.95	49.19-90.54	95
			$Ti(^3He,x)^{48}Cr$		33	7.8	9.41-134.74	95
			$Ti(\alpha,x)^{48}Cr$		65	3	20-170	95
24-Cr-51	27.704±0.04 d	EC(100)	$^{51}V(p,n)^{51}Cr$	-1.5338	10	540	6.7-13.3	96
					10.4	645	3.1-10.4	97
					11.3	834	11.3-44.7	98
					11.	595	5-11	99
					11.	729	7-15	100
					>8.1	485	1.6-8.1	101,102,103, 104,106,91
						555	7.50	105
						480	6.75	93
					<31.8	77.8	31.8-150	107
						4.8	155	8
			$^{51}V(d,2n)^{51}Cr$	-3.7585	17	678	5.58-90.5	95
			$Ti(^3He,x)^{51}Cr$		17	~25	9.74-135	95
			$Ti(\alpha,x)^{51}Cr$		16	~590	8.98-171.5	95

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
25-Mn-51	46.2±0.1 min	β^+(97),EC(3)	$^{50}Cr(p,\gamma)^{51}Mn$	5.273	2.16	0.379	0.54-3	108
			$^{52}Cr(p,2n)^{51}Mn$	-16.029		120	21.5	109
						0.91	400	110
			$^{50}Cr(d,n)^{51}Mn$	3.049		196	12	111
						Yield	3-12	112
			$^{51}V(^3He,3n)^{51}Mn$	-13.241				
25-Mn-52g	5.591±0.003 d	β^+(29),EC(71)	$^{52}Cr(p,n)^{52g}Mn$	-5.4923	12.5	203	7.5-16	113
25-Mn-52m	21.1±0.2 min	β^+(97),EC(1.25), IT(1.75)			12	350(g+m)	6-14	96
						75	12	92
					>10.5	98	5.8-10.5	97
						0.42	400	110
			$^{52}Cr(p,n)^{52m}Mn$	-5.87	12.5	410	7.5-16	113
						210	12	92
					>10.5	370	5.8-10.5	97
						0.36	400	110
			$^{52}Cr(d,2n)^{52}Mn$	-7.716	18.5	200	8.5-20	114
					>15	150	6.5-15	115
			$^{51}V(^3He,2n)^{52}Mn$	-2.704		Yield	10-14	116
26-Fe-52	8.275±0.008 h	β^+(56),EC(44)	$^{55}Mn(p,4n)^{52}Fe$	-34.374		Yield	65	117
GENERATOR			$^{59}Co(d,2p7n)^{52}Fe$	-71.847	>84.7	>0.116	68.9-84.7	118
25-Mn-52m	21.1±0.2 min	β^+(97),EC(1.25), IT(1.75)	$^{52}Cr(^3He,3n)^{52}Fe$	-16.365	34	5	10-45	119,120
			$^{50}Cr(\alpha,2n)^{52}Fe$	-15.641	28	1	20-90	119,121 122
			Ni(p,spall)^{52}Fe			1.54	800	125
			As(p,spall)^{52}Fe			0.04	590	124
			Cu(^{3}He,spall)^{52}Fe			0.2-04	258-910	123
27-Co-55	17.53±0.03 h	β^+(76),EC(24)	$^{54}Fe(p,\gamma)^{55}Co$	5.050		0.33	11	29
			$^{56}Fe(p,2n)^{55}Co$	-15.4511	23.5	65	15.6-39	126
					25	67	15.5-39	127
						105	21.5	109
			$^{54}Fe(d,n)^{55}Co$	2.8253	8	50	3-9	128
					7.5	260	4-15	129
					7.1	151	6.4-15.7	130
					7	148	4-14	250
			$^{55}Mn(^3He,3n)^{55}Co$	-12.981	28	25	14.5-39.5	131
			$^{55}Mn(\alpha,4n)^{55}Co$	-33.5594	57.77	11.6	39.8-171.15	132
			$^{52}Fe(^3He,x)^{55}Co$			Yield	0-25	133
27-Co-57	271.77±0.05 d	EC(100)	$^{60}Ni(p,\alpha)^{57}Co$	-0.2679	>13.2	40	7.4-13.2	134
					50.8	191	6.8-55	135
			daughter of ^{57}Ni (see ^{57}Ni)					
28-Ni-56	6.10±0.02 d	EC(100)	$^{56}Fe(^3He,3n)^{56}Ni$	-15.985	>29.3	2.1	19.8-29.3	136
			$^{54}Fe(\alpha,2n)^{56}Ni$	-16.062	32.5	11	16.6-40	137
					31.4	11.7	19.5-39.6	138
					>30	4	18-30	139
28-Ni-57	1.503±0.004 d	β^+(40),EC(60)	$^{58}Ni(p,pn)^{57}Ni$	-12.203	26.6	256	13.3-56.5	135
					27.77	174	11.9-44.72	140
					>18.9	110	14.2-18.9	134
						240	21.5	67
			$^{56}Fe(^3He,2n)^{57}Ni$	-5.717	18	48	7-29	136
			$^{56}Fe(\alpha,n)^{57}Ni$	-5.794	16.2	175	11-276	138
					16.6	203	6.48-40.4	137

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
29-Cu-61	3.408±0.010 h	β^+(61),EC(39)	$^{60}Ni(d,n)^{61}Cu$	2.5672				
			$^{59}Co(\alpha,2n)^{61}Cu$	-13.9723	<26	457	26-170.3	141
			$^{58}Ni(\alpha,p)^{61}Cu$	-3.1174	17	770	5-22	142
					16.9	560	9.8-27.4	143
					>11	316	4.9-11	144
			$Ni(\alpha,x)^{61}Cu$		13.2	383	8.3-38.3	143
			$^{75}As(p,spall)^{61}Cu$			7.01	800	83
29-Cu-62	9.74±0.02 min	β^+(97),EC(3)	$^{62}Ni(p,n)^{62}Cu$	-4.729	>6.66	430	4.82-6.66	145
					11.6	480	4.9-14.8	135
						9	6.07	146
			$^{59}Co(\alpha,n)^{62}Cu$	-5.077	15	676	8-19.7	147
					>11	363	5.8-11	69
			See also 30-Zn-62 - GENERATOR → 29-Cu-62					
29-Cu-67	2.580±0.004 d	β^-(100)	$^{68}Zn(p,2p)^{67}Cu$	-9.991	>430	24.9	80-430	263
					>425	24.8	130-425	59
					>85	6	30-85	85
						3.8	21.5	67
			$^{69}Ga(p,3p)^{67}Cu$	-16.599	>50.2	0.446	36.2-55.1	171
			$^{71}Ga(p,3p2n)^{67}Cu$	-33.5574	>55.3	2	19.2-55.3	171
			$^{75}As(p,x)^{67}Cu$			0.9	593	124
			$^{238}U(p,x)^{67}Cu$			2.9,2.8	11500,30000	262
			$^{67}Zn(d,2p)^{67}Cu$	-2.0163	>15.4	5.2	8.1-15.4	162
			$^{68}Zn(d,^3He)^{67}Cu$	-4.497	>15.4	0.5	11-15.4	264
			$^{64}Ni(\alpha,p)^{67}Cu$	-4.671	15.5	15.9	12.4-20.8	156
			$^{65}Cu(\alpha,2p)^{67}Cu$	-12.116	>40.1	2.7	21-40.1	167
30-Zn-62	9.26±0.02 h	β^+(8.4),EC(91.6)	$^{63}Cu(p,2n)^{62}Zn$	-13.327	27	140	17-99.2	148
↓ GENERATOR ↓					27	95	16-33	149
					26.2	218	15.2-31.8	150
					24	64	16.1-69.8	152
29-Cu-62	9.74±0.02 min	β^+(97),EC(3)			24	66	14-32.4	153
						100	21.5	109
						0.8	400	110
					<1500	0.23	1500-11500	151
			$^{63}Cu(d,3n)^{62}Zn$	-15.551	33	73	17.3-38.3	155
			$^{60}Ni(^3He,n)^{62}Zn$	3.496		Yield	0-23	154
			$^{61}Ni(^3He,2n)^{62}Zn$	-4.324				
			$^{62}Ni(^3He,3n)^{62}Zn$	-14.920				
			$^{60}Ni(\alpha,2n)^{62}Zn$	-17.083	33	230	20-39	150
					31	120	18.3-38.1	156
					>31.9	123	12.8-31.9	157
					33	134	23.3-37.7	143
			$Zn(\gamma,xn)^{62}Zn$			Yield	30-60	158
			$Ni(\alpha,xn)^{62}Zn$		31	29	16-37	143
					29	36.6	17-122	86
			$Cu(^3He,spall)^{62}Zn$			1.2-2.7	258-910	123
			Rb,Br,As(p,spall)^{62}Zn			2	800	159
						0.3-1.17	593	124

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
31-Ga-66	9.49±0.08 h	β^+(57), EC(43)	^{66}Zn(p,n)^{66}Ga	-5.9575	>11.7	646	5.5-11.7	265
					>12	700	5-12	266
					12.6	661	9.5-15.9	267
						585	12	92
					>6.36	160	6.06-6.36	160
			^{68}Zn(p,3n)^{66}Ga	-23.2107	35	120	30-85	85
						2.3	400	161
			^{69}Ga(p,p3n)^{66}Ga	-29.819	49.6	235	32.8-56.5	171
			^{71}Ga(p,p5n)^{66}Ga	-46.777		3.06	55	171
			^{75}As(p,x)^{66}Ga			12.9, 12.6	540, 593	124
			Br(p,x)^{66}Ga			10.7	593	124
			Rb(p,x)^{66}Ga			6.75	593	124
			^{89}Y(p,x)^{66}Ga			4.66, 5.75	540, 593	124
			^{66}Zn(d,2n)^{66}Ga	-8.1821	>11.1	335	8.8-11.1	268
					≳16	400	9.7-15.8	269
					>15.4	880	9-15.4	162
			^{65}Cu(^{3}He,2n)^{66}Ga	-4.757	16.3	284	6.7-23.7	164
					16	187	8.1-33.8	165
					17.5	220	7.9-21.4	270
			^{64}Zn(^{3}He,p)^{66}Ga	5.356	<21.3	28.6	21.3-42.8	271
			^{63}Cu(α,n)^{66}Ga	-7.515	16.2	698	7.8-25.6	164
					19.3	441	15.2-40.1	166
					<18.9	619	18.9-23.5	267
					>10.6	154	8.4-10.6	69
			^{65}Cu(α,3n)^{66}Ga	-25.335	>37.0	170	29.3-37	166
					>40.1	418	28-40	167
			^{64}Zn(α,pn)^{66}Ga	-15.22	31.4	753	18.9-39.6	251
					31	969	19.6-36.9	169
					>23.9	413	20.1-23.9	272
			Zn(α,n)^{66}Ga		30.8	397	21.5-37.3	170
			Cu(α,xn)^{66}Ga		18.8	4.71	12.2-53.8	273
31-Ga-67	3.261±0.001 d	EC(100)	^{67}Zn(p,n)^{67}Ga	-1.783	>6.37	420	2.34-6.37	160
					>5.34	130	1.845-5.34	102
			^{68}Zn(p,2n)^{67}Ga	-11.9823	20	430	15-85	85
						780	21.5	109
						2.34	400	161
			^{66}Zn(d,n)^{67}Ga	3.0463	8	450	1.5-15.5	162
					8.8	221	4.5-11.3	163
			^{65}Cu(^{3}He,n)^{67}Ga	6.471	12	13	8.4-23.7	164
					11.8	7.68	8.1-69.4	165
			^{65}Cu(α,2n)^{67}Ga	-14.107	27	520	16.4-36.6	166
					28.5	630	15.2-40.1	167
					≳26.5	967	11.3-26.5	164
					26.7	897	18.4-60	168
			^{64}Zn(α,p)^{67}Ga	-3.995	18.5	515	13.4-39.6	251
					18-20	452	9.1-36.9	169
			Zn(α,x)^{67}Ga		19.2	277	12-37	170
			As(p,spall)^{67}Ga			28.4	800	83
			Rb,Br(p,spall)^{67}Ga			41	800	83

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
32-Ge-68	270.8±0.3 d	EC(100)	$^{69}Ga(p,2n)^{68}Ge$	-11.479	22	490	13-55	171
						360	21.5	109
GENERATOR								
31-Ga-68	1.135±0.005 h	β^+(89),EC(11)	$^{71}Ga(p,4n)^{68}Ge$	-32.703	42.4	134	37-55	171
			$^{69}Ga(d,3n)^{68}Ge$	-13.704				
			$^{66}Zn(^3He,n)^{68}Ge$	4.663				
			$^{67}Zn(^3He,2n)^{68}Ge$	-2.391				
			$^{68}Zn(^3He,3n)^{68}Ge$	-12.590				
			$^{66}Zn(\alpha,2n)^{68}Ge$	-15.915				
			$^{68}Zn(\alpha,4n)^{68}Ge$	-33.168				
			$Ge(p,pxn)^{68}Ge$		37	100	24-64	172
			$Zn(\alpha,xn)^{68}Ge$		31	150	20-38	170
			$Y,Rb,Br,As(p,spall)^{68}Ge$			19	800	159
						6.7-11.1	593	124
34-Se-72	8.40±0.08 d	EC(100)	$^{75}As(p,4n)^{72}Se$	-30.40	~50	120	35-50	173
						1.82	400	161
GENERATOR								
33-As-72	1.083±0.004 d	β^+(88),EC(12)	$^{70}Ge(\alpha,2n)^{72}Se$	-16.63	34.1	324	20.7-41.1	174
					34	1610 (calculated)	20-40	176
			$Ge(^3He,xn)^{72}Se$		35	70	20-40	173
			$Ge(\alpha,xn)^{72}Se$		33	70	20-40	173
			$Y,Rb,Br,As(p,spall)^{72}Se$			1.4-6.0	593	124
						12	800	159
34-Se-73	7.15±0.08 h	β^+(66),EC(34)	$^{75}As(p,3n)^{73}Se$	-21.742	35	350	25-50	173
						4.32	400	161
			$^{75}As(d,4n)^{73}Se$	-23.966	41.2	77	27.4-51.3	177
			$^{72}Ge(^3He,2n)^{73}Se$	-5.579	22.5	309	16.5-36.5	175
			$^{73}Ge(^3He,3n)^{73}Se$	-12.363	>36.5	1498	32.5-36.5	175
			$^{70}Ge(\alpha,n)^{73}Se$	-7.993	23.5	504	13.0-31.5	175
			$^{72}Ge(\alpha,3n)^{73}Se$	-26.157	>39.5	435	31.5-39.5	175
			$Ge(^3He,x)^{73}Se$		20	106	10-40	173
			$Ge(\alpha,x)^{73}Se$		21	180	10-40	173
34-Se-75	119.77±0.01 d	EC(100)	$^{75}As(p,n)^{75}Se$	-1.647	>5.7	251	1.7-5.7	102,104
					7-8	447	3.6-8.1	101
						1.40	400	161
						1.88,1.9	540, 593	124
			$Br(p,x)^{75}Se$			31.9	593	124
			$Rb(p,x)^{75}Se$			24.6	593	124
			$^{89}Y(p,x)^{75}Se$			17.8,18.7	540,593	124
			$^{90}Zr(p,x)^{75}Se$			23.9	1000	274
			$^{91}Zr(p,x)^{75}Se$			22.8	1000	274
			$^{94}Zr(p,x)^{75}Se$			20.5	1000	274
			$^{75}As(d,2n)^{75}Se$	-3.8718	16.8	523	10.2-49.4	177
			$^{76}Se(^3He,\alpha)^{75}Se$	9.4172	>35.1	88.9	10.2-35.1	188
			$^{77}Se(^3He,\alpha n)$	1.9987	22.65	98.90	15-35.4	188

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
35-Br-75	1.62±0.03 H	β^+(71),EC(29)	$^{74}Se(p,\gamma)^{75}Br$	4.231	>3	2.3	1.6-3	108
			$^{76}Se(p,2n)^{75}Br$	-14.954	21.4	520	16.5-34.5	178
			$^{74}Se(d,n)^{75}Br$	2.006				
			$^{76}Se(d,3n)^{75}Br$	-19.78	30.7	370	21.28-44.27	178
			$^{75}As(^3He,3n)^{75}Br$	-13.158	25	203	15.77-41.39	178
					31	186	17.9-35.7	179
					28.5	352	15.2-62.2	180
			$^{75}As(\alpha,4n)^{75}Br$	-33.737	55	186	40.3-71.7	178
					53.8	268	42.6-106	180
			$^{65}Cu(^{12}C,2n)^{75}Br$					
			daughter of ^{75}Kr					
			$^{75}Kr \xrightarrow[(4.3\ min)]{\beta+,EC} {}^{75}Br$					
			$^{79,81}Br(p,xn)^{75}Kr$					
			$^{79,81}Br(d,xn)^{75}Kr$		76	4	60-86	181
35-Br-76	16.2±0.2 h	β^+(54),EC(46)	$^{75}As(^3He,2n)^{76}Br$	-4.09	15.9	205	9.1-37	178
					15.3	216	12.6-70.9	180
					20	141	14.65-35.87	179
			$^{75}As(\alpha,3n)^{76}Br$	-24.67	38	400	37.9-71.7	178
					34	154	28.7-105.8	180
					>35	430	30-35	182
35-Br-77	2.37650±0.00025 d	β^+(0.74), EC(99.26)	$^{77}Se(p,n)^{77}Br$	-2.147	>5.54	328	2.19-5.54	102
					<9.9	232	9.9-24.6	183
			$^{78}Se(p,2n)^{77}Br$	-12.644	22	800	13.68-24.58	183
			$^{75}As(\alpha,2n)^{77}Br$	-13.5112	26.3	803	13.8-28.1	184
					≥26.1	690	26.1-125.5	180
					25	950	20-40	182
			$Se(p,x)^{77}Br$		20	238	10-50	182
					45	174		
			$^{93}Nb(p,spall)^{77}Br$			Yield	590	83
			daughter of ^{77}Kr					
			$^{77}Kr \xrightarrow[(1.24\ h)]{\beta+,EC} {}^{77}Br$					
			See ^{77}Kr					
36-Kr-77	1.24±0.01 h	β^+(87), EC(13)	$^{79}Br(p,3n)^{77}Kr$	-22.763	35.7	178	24.6-64.7	185
					36	150	23-51	182
					35	260	25-85	186
			$^{81}Br(p,5n)^{77}Kr$	-40.806	60	41	45-85	186
			$^{79,81}Br(d,xn)^{77}Kr$		43	58	20-90	187
			$^{76}Se(^3He,2n)^{77}Kr$	-6.229	~22	370	13.15-35.05	188
			$^{77}Se(^3He,3n)^{77}Kr$	-13.648	31	356	18.06-35.72	188
36-Kr-79	1.460±0.004 d	β^+(7.1),EC(92.9)	$^{79}Br(p,n)^{79}Kr$	-2.414	<10	690	10-85	186
					10.98	724	3-24.82	189
						85.6	6.75	93
						1050	12	92
			$^{81}Br(p,3n)^{79}Kr$	-20.457	30	480	25-85	186
			$^{79,81}Br(d,xn)^{79}Kr$		20	450	10-86	187
					38	150		

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
37-Rb-81	4.58±0.01 h	β^+(31),EC(69)	$^{82,83}Kr(p,xn)^{81}Rb$			Yield	16-32	191
GENERATOR			$^{85}Rb(p,p4n)^{81}Rb$	-39.03	69.9	200	46.6-69.9	190
36-Kr-81m	13±1 s	IT(100)	$^{80}Kr(d,n)^{81}Rb$	2.59				
			$^{79}Br(\alpha,2n)^{81}Rb$	-14.37	30	380	13-38	192
			$Kr(p,xn)^{81}Rb$		27	Yield	10-45	193
			$Br(^3He,xn)^{81}Rb$		27	350	12-37	192
			daughter of ^{81}Sr					
			$^{81}Sr \xrightarrow[(22.15\ min)]{\beta+} {}^{81}Rb$					
			$^{85}Rb(p,5n)^{81}Sr$	-43.61	68 68	28 Yield	49-69.9 20-150	190 194
38-Sr-82	25.55±0.15 d	EC(100)	$^{85}Rb(p,4n)^{82}Sr$	-31.56	50	230	33.7-69.9	190
GENERATOR			$Kr(^3He,xn)^{82}Sr$		>33	42	11-33	195
37-Rb-82	1.273±0.002 min	β^+(95),EC(5)	$Kr(\alpha,xn)^{82}Sr$		>24.5	60	17.2-24.5	195
			$Rb,Mo(p,spall)^{82}S$			2.1;24.5	800	159,196
			$Rb,Y(p,spall)^{82}Sr$			2.6;19.7	593	124
			$Zr,Nb,Mo(p,spall)^{82}Sr$			Yield	800	83
			$Mo(p,spall)^{82}Sr$			15,24.5	590,800	83
38-Sr-85g	64.84±0.02 d	EC(100)	$^{88}Sr(p,p3n)^{85g}Sr$	-31.027	54	230	42-85	197
38-Sr-85m	1.1258±0.0012 h	IT(87), EC(13)	$^{89}Y(p,x)^{85g}Sr$			51.5	593	124
			$Rb(p,x)^{85g}Sr$			2.28	593	124
			$^{88}Sr(p,p3n)^{85m}Sr$	-31.266	48	41	42-85	197
			$^{90}Zr(p,3p3n)^{85m}Sr$	-46.699	>86	34	38-86	275
			$^{89}Y(p,x)^{85m}Sr$			7.5,7.2	540, 593	124
			$Rb(p,x)^{85m}Sr$			0.66	593	124
			$Kr(^3He,xn)^{85m}Sr$		16	45	11-33	195
			$Kr(\alpha,xn)^{85m}Sr$		17-21	~13	17-25	195
			$^{89}Y(p,x)^{85}Sr$			39.6,39.2	540, 593	124
			$Rb(p,x)^{85}Sr$			2.94	593	124
			$^{88}Sr(p,p3n)^{85}Sr$	-31.027	54	250	42-85	197
			$Mo(p,x)^{85}Sr$			50	800	196
			$^{238}U(p,x)^{85}Sr$			6.3	300000	262
			$Kr(^3He,xn)^{85}Sr$		~18	~200	11-33	195
			$Kr(\alpha,xn)^{85}Sr$		~22	~160	9.2-24.5	195
39-Y-87	3.346±0.013 d	β^+(0.2),EC(99.8)	$^{87}Sr(p,n)^{87}Y$	-2.664	>6.8	324	2.6-6.8	145
GENERATOR			$^{88}Sr(p,2n))^{87}Y$	-13.778	25	1210	15-33	197
38-Sr-87m	2.795±0.013 h	EC(0.3),IT(99.7)	$^{89}Y(p,p2n)^{87}Y$	-20.845	45	395	24.8-85	198
			$^{86}Sr(d,n)^{87}Y$	3.539				
			daughter of ^{87m}Y					
			$^{87m}Y \xrightarrow[(12.9\ h)]{IT} {}^{87g}Y$					
			$^{87}Rb(^3He,3n)^{87m}Y$	-11.2	25	30	12-37	199
			$^{85}Rb(\alpha,2n)^{87m}Y$	-12.2	29 25	700 450	15-40 15-38	199 200

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
40-Zr-89g	3.268±0.003 d	EC(77), β^+(23)	$^{89}Y(p,n)^{89g}Zr$	-3.6166	14.4	338	6.38-19.9	276
40-Zr-89m	4.18±0.01 min	IT(93.8), β^+(1.5), EC(4.7)			>6.73	213	3.55-6.73	145
			$^{90}Zr(p,x)^{89g}Zr$			45.4	1000	274
			$^{91}Zr(p,x)^{89g}Zr$			29.5	1000	274
			$^{94}Zr(p,x)^{89g}Zr$			89	1000	274
			$^{90}Zr(\alpha,\alpha n)^{89g}Zr$	-11.983	>78.1	423	27.5-78.1	279
			$^{89}Y(p,n)^{89m}Zr$	-4.2043	11.4	343	6.88-19.7	276
						170	12	92
			$^{89}Y(p,n)^{89}Zr$	-3.6166		750	12	92
						254, 323	7, 8.1	101
					>5.84	10.2	3.66-5.84	277
					12.8	688	3.9-44.2	278
					12	720	5-85	198
						2.69,2.74	540, 593	124
						1.85	400	161
43-Tc-95g	20.0±0.1 h	EC(100	$^{95}Mo(p,n)^{95g}Tc$	-2.484	>6.8	110	3.6-6.8	145
43-Tc-95m	61±2 d	IT(4),EC(92.9) β^+(3.1)	$^{96}Mo(P,2n)^{95g}Tc$	-11.638	20	1111	15-65	280
			$^{94}Mo(d,n)^{95g}Tc$	2.667	>4.9	35.5	0-4.9	281
					9.8	219	5.1-11.8	282
			$Mo(d,x)^{95g}Tc$		>12.7	660	0-12.7	281
			$^{93}Nb(\alpha,2n)^{95g}Tc$	-14.913	27	860	18-41	283
					27	1485	18-48	284
					26.8	855	19.1-42.1	285
			$^{92}Mo(\alpha,p)^{95g}Tc$	-5.660	20	212	12-27	168
					>19.1	161	11.5-19.1	202
			$^{94}Mo(\alpha,p2n)^{95g}Tc$	-23.405	51	545	29.8-55	168
			$^{95}Mo(p,n)^{95m}Tc$	-2.523	>6.8	60	3.6-6.8	145
			$^{96}Mo(p,2n)^{95m}Tc$	-11.677	20	396	15-65	280
			$^{94}Mo(d,n)^{95m}Tc$	2.628		0.96,18.8	3.4, 4.9	281
			$Mo(d,x)^{95m}Tc$		>12.7	154	3.4-12.7	281
			$^{93}Nb(\alpha,2n)^{95m}Tc$	-14.952	25	76	18-41	283
					27	127	18-48	284
					23-26.6	99.1	19-41.9	285
			$^{92}Mo(\alpha,p)^{95m}Tc$	-5.699	19.4	26	9.6-27.8	202
					18.8	32	13-31.5	168
			$^{94}Mo(\alpha,p2n)^{95m}Tc$	-23.444	47	46	34-56	168
			$^{95}Mo(p,n)^{95}Tc$	-2.484	>9	586.7	6-9	286
			$^{96}Mo(p,2n)^{95}Tc$	-11.638	20	1507	15-80	280
			$^{93}Nb(\alpha,2n)^{95}Tc$	-14.913	27	1612	18-48	284
43-Tc-96g	4.28±0.07 d	EC(100)	$^{96}Mo(p,n)^{96g}Tc$	-3.720	15	62	10-65	280
43-Tc-96m	51.5±1 min	IT(98),EC(2)	$^{93}Nb(\alpha,n)^{96g}Tc$	-7.000	15.2	175	13.1-26.2	285
			$^{96}Mo(p,n)^{96m}Tc$	-3.754	≤10	484	10-65	280
			$^{93}Nb(\alpha,n)^{96m}Tc$	-7.034	18.1	141	13.6-26.5	285
			$^{96}Mo(p,n)^{96}Tc$	-3.720	15	522	10-80	280
			$^{95}Mo(d,n)^{26}Tc$	3.210	>5.2	56.4	0-5.2	281
			$Mo(d,x)^{96}Tc$		>12.7	666	0-12.7	281
			$^{93}Nb(\alpha,n)^{96}Tc$	-7.000	>11	23.6	8.6-11	69
					>16.81	830	11.86-16.81	305
					18	350	15-41	283
					18	786	14.7-21.1	284
			$^{94}Mo(\alpha,pn)^{96}Tc$		33	280	20.6-59	168
			$^{95}Mo(\alpha,p2n)^{96}Tc$		44	358	27.9-60	168

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
44-Ru-94	51.8±0.6 min	EC(100)	$^{92}Mo(\alpha,2n)^{94}Ru$	-17.958	30	397	19-41	168
			$Mo(^{3}He,xn)^{94}Ru$		≥38	30	14-38	201
44-Ru-95	1.64±0.01 h	β^+(13.7), EC(86.63)	$^{92}Mo(\alpha,n)^{95}Ru$	-9.005	20	574	12-30	168
					19.1	370	9-26.5	202
			$Mo(^{3}He,xn)^{95}Ru$		33	100	14-38	201
					>38	95		
44-Ru-97	2.88±0.04 d	EC(100)	$^{94}Mo(\alpha,n)^{97}Ru$	-8.01	18	702	12-59	168
			$^{95}Mo(\alpha,2n)^{97}Ru$	-15.39	28	1293	18.4-60	168
			$Mo(^{3}He,xn)^{97}Ru$		>38	190	14-38	201
45-Rh-101m	4.34±0.01 d	EC(92.3),IT(7.7)	$^{101}Ru(p,n)^{101m}Rh$	-1.32	>6.19	132	2.9-6.19	145
						365	12	92
			daughter of ^{101}Pd					
			$^{101}Pd \xrightarrow[(8.47\ h)]{EC,\beta^-} {}^{101m}Rh$					
			$^{103}Rh(p,3n)^{101}Pd$	-19.53	32	Yield	25-37	203
46-Pd-100	3.63±0.09 d	EC(100)	$^{238}U(p,x)^{100}Pd$			0.85	300	262
48-Cd-107	6.50±0.02 h	EC(99.8), β^+(0.2)	$^{107}Ag(p,n)^{107}Cd$	-2.199	>6.4	120	3.3-6.4	160
|					≥10.5	581	1.9-10.5	97
GENERATOR					11.34	680	2.5-23.4	287
↓								
47-Ag-107m	44.3±0.2 s	IT(100)	$^{107}Ag(^{3}He,p2n)^{107}Cd$	-9.92	32.2	492	12.3-39.7	209
			$^{107}Ag(\alpha,p3n)^{107}Cd$	-30.497	54.7	530	45.5-91.8	209
			$^{109}Ag(\alpha,p5n)^{107}Cd$	-46.953	77.3	374	64.6-89.1	209
48-Cd-109	1.2665±0.0011 a	EC(100)	$^{109}Ag(d,2n)^{109}Cd$	-3.1891	13.3	930	5-16	204
|								
GENERATOR								
↓								
47-Ag-109m	39.6±0.2 s	IT(100)						
49-In-111	2.807±0.002 d	EC(100)	$^{111}Cd(p,n)^{111}In$	-1.608	>9.1	450	6.1-9.1	205
					>10.1	540	2.1-10.1	97
						810	12	92
					>6.4	200	3.04-6.4	160
					11.8	696	4.3-20.9	206
					13.1	530	4.3-14.7	207
					<70	6.55	70-400	208
			$^{112}Cd(p,2n)^{111}In$	-11.005	>20.9	1070	13.2-20.9	206
					22.8	1000	9.4-37.4	207
					<50	77.8	50-400	208
			$^{109}Ag(^{3}He,n)^{111}In$	6.564	20	2.2	10-39.6	209
					19	4	12-45	210
			$^{109}Ag(\alpha,2n)^{111}In$	-14.014	26	1200	15-36	166
					30.3	872	20.4-53.9	211
					>18.4	209	14.1-18.4	212
50-Sn-113	115.09±0.04 d	EC(100)	$^{113}In(p,n)^{113}Sn$	-1.808				
|								
GENERATOR								
↓								
49-In-113m	1.658±0.001 h	IT(100)	$^{115}In(p,3n)^{113}Sn$	-18.15				
			$^{113}In(d,2n)^{113}Sn$	-4.032				
			$^{112}Cd(^{3}He,2n)^{113}Sn$	-3.472				
			$^{113}Cd(^{3}He,3n)^{113}Sn$	-10.012				
			$^{111}Cd(\alpha,2n)^{113}Sn$	-14.653				
			$Cd(^{3}He,xn)^{113}Sn$		38	400	5-120	213
			$In(^{3}He,pxn)^{113}Sn$		55	850	20-115	213
			$Cd(\alpha,xn)^{113}Sn$		55	270	10-140	213
			$In(\alpha,pxn)^{113}Sn$		85	700	40-135	213

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
50-Sn-117m	13.61±0.04 d	IT(100)	$^{116}Cd(^{3}He,2n)^{117m}Sn$	0.1513	19.4	28	13.2-33.5	288
			$^{116}Cd(\alpha,3n)^{117m}Sn$	-20.427	34-36	1356	18-42.5	288
			$^{238}U(p,f)^{117m}Sn$			6.81	450	289
52-Te-118	6.00±0.02 d	EC(100)	$^{121}Sb(p,4n)^{118}Te$	-26.93	44	700 (calculated)		214
GENERATOR								
51-Sb-118	3.6±0.1 min	β^+(74),EC(26)	$^{123}Sb(p,6n)^{118}Te$	-42.704				
			$^{117}Sn(^{3}He,2n)^{118}Te$	-3.95				
			$^{118}Sn(^{3}He,3n)^{118}Te$	-13.28				
			$^{116}Sn(\alpha,2n)^{118}Te$	-17.59	>29.7	1500	19.7-29.7	215
54-Xe-122	20.1±0.1 h	EC(100)	$^{127}I(p,6n)^{122}Xe$	-45.06	70	114	55-85	216
GENERATOR					>67.5	197	50-67.5	223,252
						2.6	660	217
53-I-122	3.62±0.06 min	β^+(77),EC(23)	$^{127}I(d,7n)^{122}Xe$	-47.28	85	190	62.5-89	218
			$^{122}Te(^{3}He,3n)^{122}Xe$	-14.52				
			Cs,Ba,La(p,spall)^{122}Xe			2.6-25	320-660	219,217
53-I-123	13.2±0.1 h	EC(100)	$^{123}Te(p,n)^{123}I$	-1.98		210	11.5	224
			$^{124}Te(p,2n)^{123}I$	-11.41	24.6	1300	10-30	220,221,222
			$^{122}Te(d,n)^{123}I$	2.72	11.05	351	7.5-34	225
			$^{121,123}Sb(^{3}He,xn)^{123}I$		22.2	366	12.4-25.8	226
			$^{121}Sb(\alpha,2n)^{123}I$	-15.35	27.6	816	9.7-28.2	266
					≧26.5	1110	14.6-26.5	227
			daughter of ^{123}Xe					
			$^{123}Xe \xrightarrow[(2.08\ h)]{\beta^+,EC} {}^{123}I$					
			$^{127}I(p,5n)^{123}Xe$	-36.76	53.5	484	45.4-62.4	228
					57.5	372	46.4-75.6	229
					57.2	292	38.1-159.1	230
					55	269	45-85	216
						3.8	660	217
			$^{127}I(d,6n)^{123}Xe$	-38.99	70	290	45.6-86.7	218
			$^{123}Te(^{3}He,3n)^{123}Xe$	-13.16	26	178	20-38	231
			$^{124}Te(^{3}He,4n)^{123}Xe$	-22.58	45	162	28-52	231
			$^{122}Te(\alpha,3n)^{123}Xe$	-26.81		Yield	34-43	232,233
			$^{127}I(\alpha,x)^{123}Xe$ = ($^{127}I(\alpha,p7n)^{123}Xe$ + $^{127}I(\alpha,8n)^{123}Cs \rightarrow {}^{123}Xe$) (8.5 min)	-65.06 -70.05		Yield	85-102	234
			I(p,spall)^{123}Xe			3.8	660	217
			Cs(p,spall)^{123}Xe			29.3	660	217
					<350	40	35-590	219
			Ba(p,spall)^{123}Xe			26	660	217
					<365	30	365-590	219
			La(p,spall)^{123}Xe			31.9	660	217
					<320	30	320-59	219
						35	590	83

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
53-I-124	4.18±0.02 d	EC(77), β^+(23)	^{124}Te(p,n)^{124}I	-3.942	12.41	521	9.6-29.3	220
					14.54	456	9.95-29.2	222
						1.3	400	110
			^{125}Te(p,2n)^{124}I	-10.527		3.12	400	161
			^{126}Te(p,3n)^{124}I	-19.637		3.52	400	161
			^{127}I(p,p3n)^{124}I	-25.842	50	201	30-85	216
			Te(p,x)^{124}I		29-32	186	11.75-33.97	220
			^{127}I(d,p4n)^{124}I	-28.07	75.9	150	45.6-89.3	218
			Te(d,x)^{124}I		11.27	8.3	6.86-13.43	225
			^{123}Sb(^{3}He,2n)^{124}I	-3.077	≤12.4	43.4	12.4-25.8	226
			^{121}Sb(α,n)^{124}I	-7.883	18.28	557	11.5-26.5	227
			Sb(α,x)^{124}I =				9.7-28.2	226
			^{121}Sb(α,n)^{124}I +	-7.883	12.2	93		
			^{123}Sb(α,3n)^{124}I	-23.655	>28.2	189		
54-Xe-125	16.9±0.2 h	β^+(0.69), EC(99.31)	^{127}I(p,3n)^{125}Xe	-18.76	<45.3	295	45.3-62.4	228
					<46.4	126	46.4-75.6	229
					29.6	648	21.3-159	230
					30	820	20-85	216
						6.6	660	217
			^{127}I(d,4n)^{125}Xe	-20.99	47.4	460	24.2-89.2	218
			Te(^{3}He,xn)^{125}Xe		34	120	8-40	235
			Te(α,xn)^{125}Xe		>40	50	10-40	235
			^{127}I(α,x)^{125}Xe =			Yield	76-102	234
			(^{127}I(α,p5n)^{125}Xe +	-47.1				
			^{127}I(α,6n)^{125}Cs → ^{125}Xe) (45 min)	-50.9				
			I(p,spall)^{125}Xe			6.6	660	217
			Cs(p,spall)^{125}Xe			45	660	217
					<350	60	350-590	219
			Ba(p,spall)^{125}Xe			38	660	217
					<365	50	365-590	219
			La(p,spall)^{125}Xe			47.7	660	217
					<320	50	320	219
54-Xe-127g	36.41±0.02 d	EC(100)	^{133}Cs(p,x)^{127g}Xe		<356	88.2	356-588	219
54-Xe-127m	1.153±0.015 min	IT(100)	Ba(p,x)^{127g}Xe		≤462	73.7	368-590	219
			^{139}La(p,x)^{127g}Xe		460	72.2	317-589	219
			^{127}I(p,n)^{127}Xe	-1.446	9.92	471	3.0-24.8	189
					<20	68	20-85	216
			^{133}Cs(p,x)^{127}Xe		<351	85.4	351-588	219
			Ba(p,x)^{127}Xe		<367	72.5	367-589	219
			^{139}La(p,x)^{127}Xe		459	71.7	312-591	219
			^{127}I(d,2n)^{127}Xe	-3.671	15.8	470	6.5-89.3	218
					15	683	3.4-17.9	290
			^{139}La(p,2α5n)^{127}Xe	-36.79		53, 51	590,800	196
			^{238}U(p,f)^{127}Xe			9.5	11500	291

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
54-Xe-129m	8.89±0.02 d	IT(100)	$^{238}U(p,f)^{129}Xe$			11.2	11500	291
55-Cs-127	6.25±0	β^+(3.5),EC(96.5)	$^{127}I(\alpha,4n)^{127}Cs$	-32.616		Yield	76-90	234
					53.5	2180	36-150	237
56-Ba-128	2.43±0.05 d	EC(100)	$^{133}Cs(p,6n)^{128}Ba$	-43.98	65	290	48-68	236
GENERATOR			$^{133}Cs(d,7n)^{128}Ba$	-46.195				
55-Cs-128	3.62±0.02 min	β^+(69), EC(31)	$^{128}Xe(^3He,3n)^{128}Ba$	-13.89				
55-Cs-129	1.3358±0.0025 d	EC(100)	$^{127}I(\alpha,2n)^{129}Cs$	-15.11	25	1900	20-150	237
			daughter of ^{129}Ba					
			$^{129}Ba \xrightarrow[(2.23\ h)]{\beta^+,EC} {}^{129}Cs$					
			$^{133}Cs(p,5n)^{129}Ba$	-36.01	57	468	36.4-67	236
66-Dy-157	8.1±0.1 h	EC(100)	$Dy(p,pxn)^{157}Dy$		>87	280	38-87	292
			$^{159}Tb(d,4n)^{157}Dy$	-19.260	>26.8	298	19.7-26.8	293
			$Gd(\alpha,xn)^{157}Dy$		>27.4	174	15.5-27.4	294
69-Tm-167	9.24±0.02 d	EC(100)	$^{167}Er(p,n)^{167}Tm$	-1.53				
			$^{166}Er(d,n)^{167}Tm$	2.682				
			$^{165}Ho(\alpha,2n)^{167}Tm$	-16.07	28	730	20-40	238
					23.1	825	16-40	239
			$Er(^3He,pxn)^{167}Tm$		>40	300	20-40	238
			$Er(\alpha,pxn)^{167}Tm$		>37	390	20-37	238
			$Lu(p,spall)^{167}Tm$			54-55	590	240
			$Hf(p,spall)^{167}Tm$			37-65	590	240
			$Ta(p,spall)^{167}Tm$			48-57	590	240
			$W(p,spall)^{167}Tm$			47-50	590	240
70-Yb-169g	32.022±0.008 d	EC(100)	$^{169}Tm(p,n)^{169}Yb$	-1.689	10.5	163	3.3-43.9	278
70-Yb-169m	46±2 s	IT(100)						
74-W-178	21.5±0.1 d	EC(100)	$^{181}Ta(p,4n)^{178}W$	-22.99	36.3	772	28-44.2	241
GENERATOR			$^{177}Hf(^3He,2n)^{178}W$	-3.66				
73-Ta-178	9.31±0.03 min	β^+(1.1),EC(98.9)	$^{178}Hf(^3He,3n)^{178}W$	-11.28				
			$^{176}Hf(\alpha,2n)^{178}W$	-17.86				
75-Re-186	3.777±0.004 d	β^-(92.2),EC(7.8)	$^{186}W(p,n)^{186}Re$	-1.3763	<130	13.7	130-396	295
			$^{187}Re(p,pn)^{186}Re$	-7.3714		~67.4	250-440	296
			$^{186}W(d,2n)^{186}Re$	-3.6010	≥14	365	5.94-14	297
					12.1	434	7-15.7	298
					15.2	647	7-16.7	163
80-Hg-195m	1.73±0.03 d	EC(45.8),IT(54.2)	$^{197}Au(p,3n)^{195m}Hg$	-17.9	27	Yield	20-42	242
GENERATOR			$^{197}Au(d,4n)^{195m}Hg$	-20.2	36.1	614	32.9-79.8	243
79-Au-195m	30.5±0.2 s	IT(100)	$^{194}Pt(^3He,2n)^{195m}Hg$	-5.8				
			$^{192}Pt(\alpha,n)^{195m}Hg$	-11.8				

Radio-isotope	Half-life	Mode of Decay (%)	Reaction	Q MeV	E(σmax) MeV	σmax mb	En. Range MeV	Reference
81-Tl-201	3.046±0.008 d	EC(100)	$^{202}Hg(p,2n)^{201}Tl$	-8.95		3.8	400	161
			$^{206}Pb(p,x)^{201}Tl$					
			$Hg(p,xn)^{201}Tl$			Yield	14-50	244
			$Pb(p,spall)^{201}Tl$			54.7	800	83
			$Bi(p,spall)^{201}Tl$			63,58.9	590,800	83
			daughter of ^{201}Pb					
			$^{201}Pb \xrightarrow[(9.4\ h)]{EC} {}^{201}Tl$					
			$^{203}Tl(p,3n)^{201}Pb$	-17.23	27.4	1250	18.3-41.6	245
			$^{205}Tl(p,5n)^{201}Pb$	-31.43	45.7	1020	34.9-59	245
					45.7	880	34-58.7	246
			$Tl(p,x)^{201}Pb$		27.1	378	17.2-44.1	247
					>44.1	699		
82-Pb-203	2.169±0.004 d	EC(100)	$^{203}Tl(p,n)^{203}Pb$	-1.765				
			$^{205}Tl(p,3n)^{203}Pb$	-15.962	27.3	1310	17-59.1	245
					<36.3	275	36.3-58.8	246
			$Tl(p,x)^{203}Pb$		27.3	900	7.5-44.4	247
					14	36		
			daughter of ^{203}Bi					
			$^{203}Bi \xrightarrow[(11.76\ h)]{EC,\beta^+} {}^{203}Pb$					
			$^{204}Pb(d,3n)^{203}Bi$	-14.60	24-25	730	15.98-27.32	248
			$^{203}Tl(^3He,3n)^{203}Bi$	-13.460				
83-Bi-205	15.31±0.04 d	EC(99.9),β^+(0.1)	$^{206}Pb(p,2n)^{205}Bi$	-11.567	22	1030	12.7-63.8	299
			$^{207}Pb(p,3n)^{205}Bi$	-18.308	30.7	940	24.5-33.9	299
			$^{208}Pb(p,4n)^{205}Bi$	-25.677	40	930	33.8-46.4	299
			$^{209}Bi(p,p4n)^{205}Bi$	-29.480	72	180	47-144	300
			daughter of ^{205}Po					
			$^{205}Po \xrightarrow[(1.8\ h)]{EC,\beta^+,\alpha} {}^{205}Bi$					
			$^{209}Bi(p,5n)^{205}Po$	-33.62	50	800	39.8-59.7	299
					52	615	41-144	300
			$Pb(\alpha,x)^{205}Po$		>54.5	68.8	34.7-54.5	304
83-Bi-206	6.243±0.003 d		$^{207}Pb(p,2n)^{206}Bi$	-11.175	20.9	960	13-33.9	299
			$^{208}Pb(p,3n)^{206}Bi$	-18.544	30.8	980	24.5-46.4	299
			$^{209}Bi(p,p3n)^{206}Bi$	-22.347	57-63	175	41-144	300
					37.8	170	30.7-51.6	301
			daughter of ^{206}Po					
			$^{206}Po \xrightarrow[(8.8\ d)]{EC,\alpha} {}^{206}Bi$					
			$^{209}Bi(p,4n)^{206}Po$	-24.947	39	1220	29.6-45.2	299
					41	780	36-144	300
					38	814	30-44.1	241
					37.8	796	26.2-52	301
			$^{207}Pb(^3He,4n)^{206}Po$	-21.494	>31	431	22.1-31	302
			$^{206}Pb(\alpha,4n)^{206}Po$	-35.331	>47.5	1270	39-47	303
			$Pb(\alpha,x)^{206}Po$		>54.5	472	23-54.5	304
85-At-211	7.214±0.007 h	EC(58.3),α(41.7)	$^{209}Bi(\alpha,2n)^{211}At$	-20.338	31	980	20.6-43.3	249

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Integral Cross-Section (SIG) EXFOR INDEX

for Medical Radioisotopes Production

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
P0044002	5-B-10(P,G)6-C-11,,SIG	3.980E+05	1.970E+06	J,CJP,34,381,56	CHADWICK+	1CANCAN	11
C0052004	5-B-11(P,N)6-C-11,,SIG	4.000E+07	1.550E+08	J,NP,62,81,65	VALENTIN	2FR PAR	3
C0061006	5-B-11(P,N)6-C-11,,SIG	1.550E+08	1.550E+08	J,PL,7,163,63	VALENTIN+	2FR PAR	0
P0045002	5-B-11(P,N)6-C-11,,SIG	4.720E+06	1.500E+07	J,JPJ,15,2167,60	FURUKAWA+	2JPNTOK	63
P0001003	5-B-11(P,N)6-C-11,,SIG	2.890E+06	5.510E+06	J,PR,114,571,59	GIBBONS+	1USAORL	58
B0106002	5-B-11(P,N)6-C-11,,SIG	3.850E+07	1.520E+08	J,JPR,23,1000,62	ALBOUY+	2FR PAR	13
B0076007	5-B-11(P,N)6-C-11,,SIG	2.000E+05	9.860E+07	J,PR,88,19,52	HINTZ+	1USAHRV	31
B0094003	6-C-12(P,N+P)6-C-11,UND,SIG	5.910E+08	5.910E+08	J,NP,24,28,61	GOEBEL+	2ZZZCER	1
B0077003	6-C-12(P,N+P)6-C-11,UND,SIG,,A	9.300E+07	3.400E+08	J,PR,88,739,52	AAMODT+	1USABRK	8
B0077002	6-C-12(P,N+P)6-C-11,UND,SIG,,A	1.590E+07	3.200E+07	J,PR,88,739,52	AAMODT+	1USABRK	42
B0076005	6-C-12(P,N+P)6-C-11,UND,SIG	8.500E+06	1.040E+08	J,PR,88,19,52	HINTZ+	1USAHRV	42
B0149002	6-C-12(P,N+P)6-C-11,UND,SIG	5.070E+07	1.586E+08	J,NP,78,476,66	MEASDAY	1USAHRV	17
B0101009	6-C-12(P,N+P)6-C-11,UND,SIG,,A	3.400E+08	3.400E+08	J,PR,101,329,58	CRANDALL+	1USABRK	1
B0101002	6-C-12(P,N+P)6-C-11,UND,SIG,,A	1.700E+08	3.500E+08	J,PR,101,329,56	CRANDALL+	1USABRK	10
B0095002	6-C-12(P,N+P)6-C-11,UND,SIG	2.070E+07	5.050E+07	J,NP,49,417,63	CUMMING	1USABNL	9
B0022004	6-C-12(P,N+P)6-C-11,UND,SIG,,EVAL	5.000E+07	2.800E+10	J,ARN,13,261,63	CUMMING	1USABNL	15
B0022002	6-C-12(P,N+P)6-C-11,UND,SIG,,EVAL	5.000E+07	2.800E+10	J,ARN,13,261,63	CUMMING	1USABNL	15
C0062011	6-C-12(P,N+P)6-C-11,UND,SIG	1.550E+08	5.700E+09	J,NP,62,81,65	VALENTIN	2FR PAR	2
C0058002	6-C-12(P,N+P)6-C-11,UND,SIG	5.070E+07	1.586E+08	J,NP,78,476,66	MEASDAY	1USAHRV	17
P0051003	6-C-12(P,P+N)6-C-11,,SIG	1.800E+07	3.180E+07	J,CJP,36,1276,58	WHITEHEAD+	1CANCAN	36
P0051002	6-C-12(P,P+N)6-C-11,,SIG	2.760E+07	4.180E+07	J,CJP,36,1276,58	WHITEHEAD+	1CANCAN	31
R0025002	7-N-14(P,A)6-C-11,IND,SIG	5.000E+06	2.200E+07	J,PR/C,9,2134,74	JACOBS+	1USAWAU	104
R0010002	7-N-14(P,A)6-C-11,,SIG	4.650E+06	1.472E+07	J,RCA,25,17,78	CASELLA+	1USABLN	29
C0061013	7-N-14(P,A)6-C-11,UND,SIG	1.550E+08	1.550E+08	J,PL,7,163,63	VALENTIN+	2FR PAR	1
A0166003	5-B-10(D,N)6-C-11,,SIG	2.930E+06	1.099E+07	J,YK,,(2),55,84	GUZHOVSKIJ+	4CCPCCP	17
A0174004	5-B-10(D,N)6-C-11,PAR,SIG,G	9.700E+04	1.700E+05	J,NP/A,376,379,82	CECIL+	1USACSM	7
D0026002	5-B-10(D,N)6-C-11,,SIG	5.000E+05	3.200E+06	J,RCA,12,(2),75,69	WOHLLEBEN+	2GERSIE	22
P0108002	6-C-12(HE3,A)6-C-11,,SIG	1.560E+06	5.780E+06	J,NP,77,472,66	CIRILOV+	2UK MAN	77
P0050002	6-C-12(P,G)7-N-13,,SIG	8.500E+04	1.300E+05	J,PR,107,550,57	LAMB+	1USALRL	11
B0047002	6-C-12(P,G)7-N-13,,SIG	5.000E+06	1.100E+07	J,PR,100,206,55	COHEN	1USAORL	2
P0001008	6-C-13(P,N)7-N-13,,SIG	3.880E+06	5.270E+06	J,PR,114,571,59	GIBBONS+	1USAORL	59
C0062005	6-C-13(P,N)7-N-13,,SIG	1.550E+08	1.550E+08	J,NP,62,81,65	VALENTIN	2FR PAR	1
C0070003	6-C-13(P,N)7-N-13,,SIG	3.239E+06	4.250E+06	R,NFL-6,79	RAMSTROM	2SWDSWR	86
P0051004	8-O-16(P,A)7-N-13,,SIG	6.220E+06	1.560E+07	J,CJP,36,1276,58	WHITEHEAD+	1CANCAN	60
P0045003	8-O-16(P,A)7-N-13,,SIG	9.730E+06	1.500E+07	J,JPJ,15,2167,60	FURUKAWA+	2JPNTOK	32
B0157002	8-O-16(P,A)7-N-13,,SIG	6.700E+06	9.270E+06	J,NP/A,286,523,77	GRUHLE+	2GERKLN	29
C0061018	8-O-16(P,A)7-N-13,UND,SIG	1.550E+08	1.550E+08	J,PL,7,163,63	VALENTIN+	2FR PAR	1
P0130002	6-C-12(D,N)7-N-13,,SIG	1.960E+06	1.630E+08	J,PR,181,1428,69	JASZCZAK+	1USAORL	401
P0001005	5-B-10(A,N)7-N-13,,SIG	2.550E+06	4.830E+06	J,PR,114,571,59	GIBBONS+	1USAORL	37
B0125002	7-N-14(D,N)8-O-15,,SIG	6.000E+05	1.435E+07	J,RCA,24,65,77	VERA RUIZ+	1USABNL	33
D0025002	7-N-14(D,N)8-O-15,,SIG	6.000E+05	1.435E+07	J,RCA,24,65,77	VERA RUIZ+	1USABNL	27
D0026003	7-N-14(D,N)8-O-15,,SIG	5.000E+05	3.200E+06	J,RCA,12,(2),75,69	WOHLLEBEN+	2GERSIE	22
P0133002	6-C-12(A,N)8-O-15,,SIG	1.140E+07	2.270E+07	J,NP,115,683,68	BLACK+	1USASTF	246

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A0235002	8-O-18(P,N)9-F-18,IND,SIG	2.300E+06	1.471E+07	J,RCA,26,21,79	RUTH+	1USABNL	35
A0175002	10-NE-20(D,X)9-F-18,CUM,SIG	2.469E+07	7.602E+07	J,RCA,29,1,61	BACKHAUSEN+	2GERJUL	24
A0175002	10-NE-20(D,A)9-F-18,IND,SIG	2.469E+07	7.602E+07	J,RCA,29,1,61	BACKHAUSEN+	2GERJUL	24
B0151002	8-O-16(HE3,P)9-F-18,CUM,SIG	7.700E+06	4.030E+07	J,ARI,28,781,77	FITSCHEN+	2GERHAM	19
A0175002	10-NE-20(D,3N+P)10-NE-18,IND/UND,SIG	2.469E+07	7.602E+07	J,RCA,29,1,61	BACKHAUSEN+	2GERJUL	24
R0023003	10-NE-20(HE3,N+A)10-NE-18,IND,SIG	1.810E+07	3.070E+07	J,RCA,29,1,61	BACKHAUSEN+	2GERJUL	9
A0175004	10-NE-20(HE3,N+A)10-NE-18,IND,SIG	1.644E+07	3.069E+07	J,RCA,29,1,61	BACKHAUSEN+	2GERJUL	9
A0175003	10-NE-20(HE3,N+A)10-NE-18,IND,SIG	1.727E+07	3.240E+07	J,RCA,29,1,61	BACKHAUSEN+	2GERJUL	6
B0099002	12-MG-24(D,A)11-NA-22,,SIG	9.000E+05	1.610E+07	J,JIN,31,3345,69	ROEHM+	3SAFNLP	33
A0188006	9-F-19(A,N)11-NA-22,,SIG,,EVAL	2.400E+06	8.000E+06	J,VAT/D,,(4),31,83	VUKOLOV+	4CCPKUR	31
P0040006	14-SI-30(P,3P)12-MG-28,,SIG	1.300E+08	4.250E+08	J,PR,127,1731,62	MORRISON+	1USACAR	5
P0040012	15-P-31(P,4P)12-MG-28,,SIG	1.300E+08	4.250E+08	J,PR,127,1731,62	MORRISON+	1USACAR	5
P0040018	16-S-32(P,5P)12-MG-28,,SIG	1.300E+08	4.000E+08	J,PR,127,1731,62	MORRISON+	1USACAR	2
P0123002	12-MG-26(A,2P)12-MG-28,,SIG	1.890E+07	3.660E+07	J,PR,118,1203,60	LINDSAY+	1USAWSU	17
B0174009	12-MG-26(A,2P)12-MG-28,,SIG	1.720E+07	1.520E+08	J,ARI,27,431,76	PROBST+	2GERJUL	33
B0174008	13-AL-27(A,3P)12-MG-28,,SIG	2.940E+07	1.600E+08	J,ARI,27,431,76	PROBST+	2GERJUL	67
B0142008	13-AL-27(A,3P)12-MG-28,,SIG	3.570E+07	1.023E+08	J,ZP,233,170,70	MARTENS+	2GERKFK	35
P0040017	16-S-0(P,X)12-MG-28,,SIG	1.300E+08	4.250E+08	J,PR,127,1731,62	MORRISON+	1USACAR	5
B0049006	15-P-31(P,N+P)15-P-30,UND,SIG	2.150E+07	2.150E+07	J,PR,99,723,55	COHEN+	1USAORL	1
A0181004	15-P-31(P,N+P)15-P-30,CUM/UND,SIG	1.960E+07	3.440E+07	J,ARI,30,3,79	SAHAKUNDU+	2GERJUL	11
P0070012	13-AL-27(A,N)15-P-30,,SIG	5.200E+06	1.100E+07	J,PR/B,133,911,64	STELSON+	1USAORL	30
A0161005	13-AL-27(A,N)15-P-30,IND,SIG	1.050E+07	2.760E+07	J,ARI,30,3,79	SAHAKUNDU+	2GERJUL	15
A0171029	13-AL-27(A,N)15-P-30,IND,SIG	0.000E+00	3.440E+07	J,PR/C,25,770,82	FRANTSVOG+	1USACLU	5
A0171036	14-SI-28(A,D)15-P-30,UND,SIG	0.000E+00	3.440E+07	J,PR/C,25,770,82	FRANTSVOG+	1USACLU	4
B0049007	17-CL-35(P,N+P)17-CL-34-M,UND,SIG	2.150E+07	2.150E+07	J,PR,99,723,55	COHEN+	1USAORL	1
A0240002	16-S-32(HE3,P)17-CL-34,(CUM),SIG	3.800E+06	2.210E+07	J,RCA,19,159,74	LEE+	1USABRK	15
A0240003	17-CL-37(HE3,2N)19-K-38,IND,SIG	7.300E+06	2.020E+07	J,RCA,19,159,74	LEE+	1USABRK	14
A0240005	20-CA-40(HE3,P+A)19-K-38,(CUM),SIG	8.100E+06	2.020E+07	J,RCA,19,159,74	LEE+	1USABRK	8
P0125003	18-AR-40(A,P)19-K-43,,SIG	1.160E+07	3.670E+07	J,JPJ,15,952,60	TANAKA+	2JPNTOK	9

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
A0159013	23-V-51(A,3N+5P)20-CA-47,CUM/UND,SIG	8.177E+07	1.710E+08	C,82ANTWER,,599,8209	MICHEL+	2GERKLN	12
B0026003	92-U-238(P,X)20-CA-47,CUM,SIG	3.000E+11	3.000E+11	J,PR/C,9,1138,74	CHANG+	1USACHI	1
B0053008	21-SC-45(P,2N)22-TI-44,,SIG	1.500E+07	8.500E+07	J,NP/A,150,11,70	MCGEE+	1CANMCG	10
B0052002	21-SC-45(P,N)22-TI-45,,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
P0024002	21-SC-45(P,N)22-TI-45,,SIG	7.800E+06	1.440E+07	J,NP/A,106,323,68	THOMAS+	1USALRL	10
B0064002	21-SC-45(P,N)22-TI-45,,SIG	3.280E+06	6.770E+06	J,NP,64,513,65	DELL+	1USAOSU	11
B0061002	21-SC-45(P,N)22-TI-45,,SIG	6.750E+06	6.750E+06	J,PR,130,1522,63	HUMES+	1USAOSU	1
B0053007	21-SC-45(P,N)22-TI-45,,SIG	1.000E+07	8.500E+07	J,NP/A,150,11,70	MCGEE+	1CANMCG	11
A0169004	23-V-51(D,5N)24-CR-48,IND,SIG	4.919E+07	9.054E+07	J,ARI,31,223,80	WEINREICH+	2GERJUL	21
A0169007	22-TI-0(HE3,X)24-CR-48,IND,SIG	9.410E+06	1.347E+08	J,ARI,31,223,80	WEINREICH+	2GERJUL	55
A0169006	22-TI-0(A,X)24-CR-48,IND,SIG	1.902E+07	1.724E+08	J,ARI,31,223,80	WEINREICH+	2GERJUL	37
B0043004	23-V-51(P,N)24-CR-51,,SIG	6.700E+06	1.330E+07	J,JPJ,14,1269,59	TANAKA+	2JPNTOK	8
B0027002	23-V-51(P,N)24-CR-51,,SIG	1.130E+07	4.470E+07	J,NC/A,22,547,74	GADIOLI+	2ITYMIL	17
C0062009	23-V-51(P,N)24-CR-51,,SIG	1.550E+06	1.550E+08	J,NP,62,61,65	VALENTIN	2FR PAR	1
B0064003	23-V-51(P,N)24-CR-51,,SIG	3.740E+06	6.700E+06	J,NP,64,513,65	DELL+	1USAOSU	10
B0061003	23-V-51(P,N)24-CR-51,,SIG	6.750E+06	6.750E+06	J,PR,130,1522,63	HUMES+	1USAOSU	1
B0051005	23-V-51(P,N)24-CR-51,,SIG	4.380E+06	6.610E+06	J,PR,125,291,62	TAKETANI+	1USAROC	4
B0046004	23-V-51(P,N)24-CR-51,,SIG	1.569E+06	2.295E+06	J,PR,109,1243,58	JOHNSON+	1USAORL	59
B0068024	23-V-51(P,N)24-CR-51,,SIG	1.572E+06	5.420E+06	P,ORNL-2910,25,60	JOHNSON+	1USAORL	115
B0067002	23-V-51(P,N)24-CR-51,,SIG	7.500E+06	7.500E+06	J,PR,123,276,61	SHORE+	1USAMIT	1
B0066002	23-V-51(P,N)24-CR-51,,SIG	5.000E+06	1.100E+07	J,PR,128,291,62	HANSEN+	1USALRL	7
B0065002	23-V-51(P,N)24-CR-51,,SIG	3.100E+06	1.040E+07	J,PR,128,280,62	WING+	1USAANL	16
P0021004	23-V-51(P,N)24-CR-51,,SIG	7.000E+06	1.500E+07	J,NP,93,648,67	CHODIL+	1USALRL	17
P0015002	23-V-51(P,N)24-CR-51,,SIG	1.580E+06	2.280E+06	J,NIM,33,257,65	HARRIS+	1USALMS	14
B0106003	23-V-51(P,N)24-CR-51,,SIG	3.180E+07	1.500E+08	J,JPR,23,1000,62	ALBOUY+	2FR PAR	9
B0093002	23-V-51(P,N)24-CR-51,,SIG	3.600E+06	8.100E+06	J,PR,115,925,59	ALBERT	1USALRL	7
A0169002	23-V-51(D,2N)24-CR-51,IND,SIG	5.580E+06	9.050E+07	J,ARI,31,223,80	WEINREICH+	2GERJUL	54
A0169008	22-TI-0(HE3,X)24-CR-51,IND,SIG	9.740E+06	1.354E+08	J,ARI,31,223,80	WEINREICH+	2GERJUL	25
A0169005	22-TI-0(A,X)24-CR-51,IND,SIG	8.980E+06	1.715E+08	J,ARI,31,223,80	WEINREICH+	2GERJUL	48
A0048002	24-CR-50(P,G)25-MN-51,,SIG	5.400E+05	3.000E+06	J,IZV,41,(10),2196,77	KRIVONOSOV+	4CCPKFT	45
B0071003	24-CR-52(P,2N)25-MN-51,,SIG	4.000E+08	4.000E+08	J,JIN,31,1915,69	REULAND+	1USACAR	1
B0050003	24-CR-52(P,2N)25-MN-51,,SIG	2.150E+07	2.150E+07	J,PR,99,718,55	COHEN+	1USAORL	1

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B0071002	24-CR-52(P,N)25-MN-52-M,,SIG	4.000E+08	4.000E+08	J,JIN,31,1915,69	REULAND+	1USACAR	1
B0071002	24-CR-52(P,N)25-MN-52-G,,SIG	4.000E+08	4.000E+08	J,JIN,31,1915,69	REULAND+	1USACAR	1
B0065003	24-CR-52(P,N)25-MN-52-M,,SIG	5.800E+06	1.050E+07	J,PR,128,280,62	WING+	1USAANL	18
B0065003	24-CR-52(P,N)25-MN-52-G,,SIG	5.800E+06	1.050E+07	J,PR,128,280,62	WING+	1USAANL	18
P0043003	24-CR-52(P,N)25-MN-52-G,,SIG	7.500E+06	1.600E+07	J,PR,114,322,59	LINDER+	1USACLA	5
P0043002	24-CR-52(P,N)25-MN-52-M,,SIG	8.000E+06	1.600E+07	J,PR,114,322,59	LINDER+	1USACLA	6
A0085027	24-CR-52(P,N)25-MN-52-M,IND,SIG	6.850E+06	1.040E+07	J,AE,49,(2),101,8008	MUMINOV+	4CCPSUL	3
A0072002	24-CR-52(P,N)25-MN-52-G+M,IND,SIG/SUM	6.070E+06	6.070E+06	C,80LENGRD,,316,8003	ANTROPOV+	4CCPSUL	1
B0051003	24-CR-52(P,N)25-MN-52-M,,SIG	6.040E+06	6.570E+06	J,PR,125,291,62	TAKETANI+	1USAROC	3
B0043005	24-CR-52(P,N)25-MN-52-M,,SIG	8.400E+06	1.390E+07	J,JPJ,14,1269,59	TANAKA+	2JPNTOK	11
B0043005	24-CR-52(P,N)25-MN-52-G,,SIG	8.400E+06	1.390E+07	J,JPJ,14,1269,59	TANAKA+	2JPNTOK	11
C0062010	24-CR-52(P,N)25-MN-52.(M),SIG	1.550E+08	1.550E+08	J,NP,62,81,65	VALENTIN	2FR PAR	1
B0052003	24-CR-52(P,N)25-MN-52-M,,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
B0052003	24-CR-52(P,N)25-MN-52-G,,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
A0202003	24-CR-52(D,2N)25-MN-52-G,IND/M+,SIG	1.490E+07	2.400E+07	J,RCA,19,(3),97,73	NASSIFF+	2GERKFK	5
B0047003	26-FE-54(P,G)27-CO-55,,SIG	1.100E+07	1.100E+07	J,PR,100,206,55	COHEN	1USAORL	1
B0050006	26-FE-56(P,2N)27-CO-55,,SIG	2.150E+07	2.150E+07	J,PR,99,718,55	COHEN+	1USAORL	1
B0041004	26-FE-56(P,2N)27-CO-55,,SIG	1.560E+07	3.900E+07	J,JIN,32,1419,70	JENKINS+	2UK HAR	11
S0015003	26-FE-54(D,N)27-CO-55,,SIG	6.400E+06	1.570E+07	J,CST,5,506,63	TAO ZHENLAN+	3CPRNRS	20
B0178002	25-MN-55(HE3,3N)27-CO-55,,SIG	1.450E+07	3.950E+07	J,ARI,30,625,79	WATANABE+	2JPNTOK	39
A0159019	25-MN-55(A,4N)27-CO-55,IND,SIG	3.980E+07	1.711E+08	C,82ANTWER,,599,8209	MICHEL+	2GERKLN	16
B0055002	28-NI-60(P,A)27-CO-57,,SIG	7.400E+06	1.320E+07	J,PR,117,1532,60	KAUFMAN	1USAPTN	12
B0020011	28-NI-60(P,A)27-CO-57,UND,SIG	6.800E+06	5.500E+07	J,JIN,34,2419,72	TANAKA+	2JPNTOK	15
P0058010	26-FE-54(A,2N)28-NI-56,,SIG	1.660E+07	4.000E+07	J,PR,123,231,61	HOUCK+	1USACOL	15
P0057009	26-FE-54(A,2N)28-NI-56,,SIG	1.950E+07	3.960E+07	J,JPJ,15,1547,60	TANAKA+	2JPNTOK	14
P0057008	26-FE-54(A,2N)28-NI-56,,SIG	1.830E+07	3.140E+07	J,JPJ,15,1547,60	TANAKA+	2JPNTOK	8
B0083004	28-NI-58(P,N+P)28-NI-57,UND,SIG,,A	1.190E+07	4.472E+07	J,ZP/A,286,393,78	MICHEL+	2GERKLN	19
B0055004	28-NI-58(P,N+P)28-NI-57,UND,SIG	1.420E+07	1.890E+07	J,PR,117,1532,60	KAUFMAN	1USAPTN	16
B0049013	28-NI-58(P,N+P)28-NI-57,UND,SIG	2.150E+07	2.150E+07	J,PR,99,723,55	COHEN+	1USAORL	1
B0020002	28-NI-58(P,N+P)28-NI-57,CUM/UND,SIG	1.330E+07	5.650E+07	J,JIN,34,2419,72	TANAKA+	2JPNTOK	23
P0058008	26-FE-54(A,N)28-NI-57,,SIG	6.480E+06	4.040E+07	J,PR,123,231,61	HOUCK+	1USACOL	20
P0057002	26-FE-54(A,N)28-NI-57,,SIG	1.100E+07	2.760E+07	J,JPJ,15,1547,60	TANAKA+	2JPNTOK	15
A0147002	27-CO-59(A,2N)29-CU-61,IND,SIG	2.604E+07	1.703E+08	J,NP/A,338,167,80	MICHEL+	2GERKLN	17
P0071004	28-NI-58(A,P)29-CU-61,,SIG	7.000E+06	1.100E+07	J,PR/B,133,907,64	MCGOWAN+	1USAORL	21
P0071003	28-NI-58(A,P)29-CU-61,,SIG	4.900E+06	6.100E+06	J,PR/B,133,907,64	MCGOWAN+	1USAORL	13
B0128012	28-NI-58(A,P)29-CU-61,CUM,SIG	9.800E+06	2.740E+07	J,ARI,29,611,78	MURAMATSU+	2JPNTOK	8
B0128002	28-NI-0(A,X)29-CU-61,CUM,SIG	8.300E+06	3.830E+07	J,ARI,29,611,78	MURAMATSU+	2JPNTOK	21

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
P0033003	28-NI-62(P,N)29-CU-62,,SIG	4.820E+06	6.660E+06	J,HPA,24,441,51	BLASER+	2SWTSWT	12
B0029019	28-NI-62(P,N)29-CU-62,,SIG	4.900E+06	1.480E+07	J,JIN,34,2419,72	TANAKA+	2JPNTOK	30
A0072004	28-NI-62(P,N)29-CU-62,IND,SIG	6.070E+06	6.070E+06	C,BOLENGRAD,316,0003	ANTROPOV+	4CCPSUL	1
P0070005	27-CO-59(A,N)29-CU-62,,SIG	5.800E+06	1.100E+07	J,PR/B,133,911,64	STELSON+	1USAORL	27
P0040004	30-ZN-68(P,2P)29-CU-67,,SIG	1.300E+08	4.250E+08	J,PR,127,1731,62	MORRISON+	1USACAR	5
B0053005	30-ZN-68(P,2P)29-CU-67,,SIG	3.000E+07	8.500E+07	J,NP/A,150,11,70	MCGEE+	1CANMCG	8
B0049017	30-ZN-68(P,2P)29-CU-67,,SIG	2.150E+07	2.150E+07	J,PR,99,723,55	COHEN+	1USAORL	1
P0014012	31-GA-69(P,3P)29-CU-67,,SIG	3.620E+07	5.510E+07	J,NP,43,500,63	PORILE+	2JPNTOK	5
P0014023	31-GA-71(P,3P+2N)29-CU-67,,SIG	1.920E+07	5.530E+07	J,NP,43,500,63	PORILE+	2JPNTOK	17
D0029065	33-AS-75(P,X)29-CU-67,CUM,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
B0029004	92-U-238(P,X)29-CU-67,CUM,SIG	1.150E+10	1.150E+10	J,PR/C,6,715,73	CHANG+	1USACHI	1
B0026010	92-U-238(P,X)29-CU-67,CUM,SIG	1.150E+10	3.000E+11	J,PR/C,9,1138,74	CHANG+	1USACHI	2
P0076002	30-ZN-67(D,2P)29-CU-67,,SIG	8.100E+06	1.540E+07	J,PR,130,265,63	WILLIAMS+	1USAMIT	20
P0075003	30-ZN-68(D,HE3)29-CU-67,,SIG	1.100E+07	1.540E+07	J,PR,130,259,63	WILLIAMS+	1USAMIT	21
P0037016	28-NI-64(A,P)29-CU-67,,SIG	1.240E+07	2.080E+07	J,JPJ,15,2195,60	TANAKA	2JPNJPN	4
B0156007	29-CU-65(A,2P)29-CU-67,,SIG	2.100E+07	4.010E+07	J,PR,116,1193,59	PORILE+	1USABNL	9
B0031003	29-CU-63(P,2N)30-ZN-62,,SIG	1.500E+09	1.150E+10	J,PR/C,7,1410,73	STEINBERG+	1USAANL	7
B0017006	29-CU-63(P,2N)30-ZN-62,,SIG	1.520E+07	3.180E+07	J,PR,80,939,50	GHOSHAL	1USABRK	9
B0074002	29-CU-63(P,2N)30-ZN-62,,SIG	1.600E+07	3.300E+07	J,ARI,23,342,72	GREENE+	1USABNL	17
B0071005	29-CU-63(P,2N)30-ZN-62,,SIG	4.000E+08	4.000E+08	J,JIN,31,1915,69	REULAND+	1USACAR	1
B0054005	29-CU-63(P,2N)30-ZN-62,,SIG	1.700E+07	9.920E+07	J,PR,91,885,53	MEADOWS	1USAHRV	18
B0050010	29-CU-63(P,2N)30-ZN-62,,SIG	2.150E+07	2.150E+07	J,PR,99,718,55	COHEN+	1USAORL	1
B0121008	29-CU-63(D,3N)30-ZN-62,,SIG,,A	1.730E+07	3.830E+07	J,NP/A,155,40,70	FULMER+	1USAORL	8
P0037009	28-NI-60(A,2N)30-ZN-62,,SIG	1.830E+07	3.810E+07	J,JPJ,15,2195,60	TANAKA	2JPNJPN	15
B0164002	28-NI-60(A,2N)30-ZN-62,,SIG,,A	1.280E+07	3.190E+07	J,ARI,26,606,77	NEIRINCKX	3SAFNLP	19
B0128019	28-NI-60(A,2N)30-ZN-62,,SIG	2.330E+07	3.770E+07	J,ARI,29,611,78	MURAMATSU+	2JPNTOK	11
B0017003	28-NI-60(A,2N)30-ZN-62,,SIG	2.000E+07	3.900E+07	J,PR,80,939,50	GHOSHAL	1USABRK	8
B0060004	30-ZN-66(P,N)31-GA-66,,SIG	5.500E+06	1.170E+07	J,PR,109,2083,58	HOWE	1USACLA	16
B0058003	30-ZN-66(P,N)31-GA-66,,SIG	9.500E+06	1.590E+07	J,NP/A,198,625,72	HILLE+	2GERMUN	8
B0052007	30-ZN-66(P,N)31-GA-66,,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
B0048004	30-ZN-66(P,N)31-GA-66,,SIG	6.060E+06	6.360E+06	J,HPA,24,3,51	BLASER+	2SWTETH	3
B0053004	30-ZN-68(P,3N)31-GA-66,,SIG	3.000E+07	8.500E+07	J,NP/A,150,11,70	MCGEE+	1CANMCG	8
B0024006	30-ZN-68(P,3N)31-GA-66,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
P0014007	31-GA-69(P,P+3N)31-GA-66,,SIG	3.280E+07	5.650E+07	J,NP,43,500,63	PORILE+	2JPNTOK	15
P0014027	31-GA-71(P,P+5N)31-GA-66,,SIG	5.500E+07	5.500E+07	J,NP,43,500,63	PORILE+	2JPNTOK	1
D0029059	33-AS-75(P,X)31-GA-66,CUM,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
D0029161	35-BR-0(P,X)31-GA-66,CUM,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
D0029119	37-RB-0(P,X)31-GA-66,CUM,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
D0029037	39-Y-89(P,X)31-GA-66,CUM,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
B0154003	29-CU-65(HE3,2N)31-GA-66,,SIG	7.900E+06	2.140E+07	J,ARI,21,625,70	LEBOWITZ+	1USABNL	7
B0079005	29-CU-65(HE3,2N)31-GA-66,,SIG	6.700E+06	2.370E+07	J,PR,130,1512,63	BRYANT+	1USALAS	19
B0039003	29-CU-65(HE3,2N)31-GA-66,,SIG	8.100E+06	3.380E+07	J,NP/A,152,419,70	GOLCHERT+	1USAANL	52
P0070006	29-CU-63(A,N)31-GA-66,,SIG	8.400E+06	1.060E+07	J,PR/B,133,911,64	STELSON+	1USAORL	12
B0156002	29-CU-63(A,N)31-GA-66,,SIG	1.520E+07	4.010E+07	J,PR,116,1193,59	PORILE+	1USABNL	13
B0079016	29-CU-63(A,N)31-GA-66,,SIG	7.800E+06	2.560E+07	J,PR,130,1512,63	BRYANT+	1USALAS	19
B0058006	29-CU-63(A,N)31-GA-66,,SIG	1.890E+07	2.350E+07	J,NP/A,198,625,72	HILLE+	2GERMUN	4
P0105003	30-ZN-64(A,P+N)31-GA-66,,SIG	2.010E+07	2.390E+07	J,NP,73,122,65	COGNEAU+	2BLGLVN	7
P0073005	30-ZN-64(A,P+N)31-GA-66,,SIG	1.890E+07	3.960E+07	J,PR,115,939,59	PORILE	1USABNL	10
B0135004	30-ZN-0(A,X)31-GA-66,,SIG	2.000E+07	3.820E+07	J,ARI,29,615,78	NAGAME+	2JPNTOK	21
D0046002	29-CU-0(A,XN)31-GA-66,,SIG	1.224E+07	5.378E+07	W,S,J,NASSIFF,830124	NASSIFF	3ARGCNE	17

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B0068011	30-ZN-67(P,N)31-GA-67,,SIG	1.845E+06	5.340E+06	P,ORNL-2910,25,60	JOHNSON+	1USAORL	30
B0048005	30-ZN-67(P,N)31-GA-67,,SIG	2.340E+06	6.370E+06	J,HPA,24,3,51	BLASER+	2SWTETH	18
B0053003	30-ZN-68(P,2N)31-GA-67,,SIG	1.500E+07	8.500E+07	J,NP/A,150,11,70	MCGEE+	1CANMCG	11
B0050013	30-ZN-68(P,2N)31-GA-67,,SIG	2.150E+07	2.150E+07	J,PR,99,718,55	COHEN+	1USAORL	1
B0024005	30-ZN-68(P,2N)31-GA-67,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
A0202002	30-ZN-66(D,N)31-GA-67,IND,SIG	4.500E+06	1.130E+07	J,RCA,19,(3),97,73	NASSIFF+	2GERKFK	7
B0079006	29-CU-65(HE3,N)31-GA-67,,SIG	8.400E+06	2.370E+07	J,PR,130,1512,63	BRYANT+	1USALAS	13
B0039002	29-CU-65(HE3,N)31-GA-67,,SIG	8.100E+06	6.940E+07	J,NP/A,152,419,70	GOLCHERT+	1USAANL	80
B0156005	29-CU-65(A,2N)31-GA-67,,SIG	1.520E+07	4.010E+07	J,PR,116,1193,59	PORILE+	1USABNL	13
B0079017	29-CU-65(A,2N)31-GA-67,UND,SIG	1.130E+07	2.650E+07	J,PR,130,1512,63	BRYANT+	1USALAS	22
B0040018	29-CU-65(A,2N)31-GA-67,,SIG	1.840E+07	6.000E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	13
P0073003	30-ZN-64(A,P)31-GA-67,,SIG	1.340E+07	3.960E+07	J,PR,115,939,59	PORILE	1USABNL	11
B0135003	30-ZN-0(A,X)31-GA-67,,SIG	1.270E+07	3.600E+07	J,ARI,29,615,78	NAGAME+	2JPNTOK	22
B0097002	30-ZN-0(A,X)31-GA-67,CUM,SIG	8.800E+06	9.650E+07	R,CSIR-FIS-91,76	HAASBROEK+	3SAFNLP	13
P0014003	31-GA-69(P,2N)32-GE-68,,SIG	1.310E+07	5.500E+07	J,NP,43,500,63	PORILE+	2JPNTOK	20
B0050014	31-GA-69(P,2N)32-GE-68,,SIG	2.150E+07	2.150E+07	J,PR,99,718,55	COHEN+	1USAORL	1
P0014014	31-GA-71(P,4N)32-GE-68,,SIG	3.580E+07	5.630E+07	J,NP,43,500,63	PORILE+	2JPNTOK	8
B0024012	33-AS-75(P,4N)34-SE-72,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
D0029047	33-AS-75(P,4N)34-SE-72,IND,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
P0074002	32-GE-70(A,2N)34-SE-72,,SIG	2.070E+07	4.110E+07	J,PR,116,415,59	AMIEL	1USABNL	10
D0029046	33-AS-75(P,3N)34-SE-73-G,CUM,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
B0024011	33-AS-75(P,3N)34-SE-73-M,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
B0024011	33-AS-75(P,3N)34-SE-73-G,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
B0152003	32-GE-72(HE3,2N)34-SE-73,M+,SIG	1.650E+07	3.650E+07	J,ARI,29,611,78	GUILLAUME+	1USABNL	21
B0152005	32-GE-73(HE3,3N)34-SE-73,M+,SIG	3.250E+07	3.650E+07	J,ARI,29,611,78	GUILLAUME+	1USABNL	5
B0152002	32-GE-70(A,N)34-SE-73,M+,SIG	1.300E+07	3.150E+07	J,ARI,29,611,78	GUILLAUME+	1USABNL	12
B0152004	32-GE-72(A,3N)34-SE-73,M+,SIG	3.150E+07	3.950E+07	J,ARI,29,611,78	GUILLAUME+	1USABNL	9
D0029045	33-AS-75(P,N)34-SE-75,IND,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
B0093011	33-AS-75(P,N)34-SE-75,,SIG	3.600E+06	8.100E+06	J,PR,115,925,59	ALBERT	1USALRL	7
B0068026	33-AS-75(P,N)34-SE-75,,SIG	1.710E+06	5.705E+06	P,ORNL-2910,25,60	JOHNSON+	1USAORL	133
B0046010	33-AS-75(P,N)34-SE-75,,SIG	1.671E+06	2.169E+06	J,PR,109,1243,58	JOHNSON+	1USAORL	66
B0024010	33-AS-75(P,N)34-SE-75,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
D0029145	35-BR-0(P,X)34-SE-75,IND,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
D0029105	37-RB-0(P,X)34-SE-75,IND,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
D0029027	39-Y-89(P,X)34-SE-75,IND,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
A0041003	40-ZR-90(P,X)34-SE-75,CUM,SIG	1.000E+09	1.000E+09	J,IZV,42,(11),2392,78	BELJAEV+	4CCPFTI	12
A0041003	40-ZR-91(P,X)34-SE-75,CUM,SIG	1.000E+09	1.000E+09	J,IZV,42,(11),2392,78	BELJAEV+	4CCPFTI	12
A0041003	40-ZR-94(P,X)34-SE-75,CUM,SIG	1.000E+09	1.000E+09	J,IZV,42,(11),2392,78	BELJAEV+	4CCPFTI	12
A0154007	34-SE-76(HE3,A)34-SE-75,IND/UND,SIG	1.017E+07	3.514E+07	J,ARI,33,13,82	HE YOUFENG+	2GERJUL	12
A0154006	34-SE-77(HE3,N+A)34-SE-75,IND/UND,SIG	1.496E+07	3.540E+07	J,ARI,33,13,82	HE YOUFENG+	2GERJUL	11

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A0048009	34-SE-74(P,G)35-BR-75,,SIG	1.600E+06	3.000E+06	J,IZV,41,(10),2196,77	KRIVONOSOV+	4CCPKFT	8
A0253003	34-SE-76(P,2N)35-BR-75,IND,SIG	1.650E+07	3.449E+07	J,ARI,31,267,80	PAANS+	2NEDGRN	11
A0253006	34-SE-76(D,3N)35-BR-75,IND,SIG	2.128E+07	4.427E+07	J,ARI,31,267,80	PAANS+	2NEDGRN	8
A0253009	33-AS-75(HE3,3N)35-BR-75,IND,SIG	1.577E+07	4.139E+07	J,ARI,31,267,80	PAANS+	2NEDGRN	9
A0232003	33-AS-75(HE3,3N)35-BR-75,IND,SIG	1.520E+07	6.218E+07	J,RCA,30,67,82	ALFASSI+	2GERJUL	50
A0160002	33-AS-75(HE3,3N)35-BR-75,IND,SIG	1.792E+07	3.569E+07	C,79INNSBR,,202,80	WEINREICH+	2GERJUL	18
A0253012	33-AS-75(A,4N)35-BR-75,IND,SIG	4.030E+07	7.173E+07	J,ARI,31,267,80	PAANS+	2NEDGRN	9
A0232008	33-AS-75(A,4N)35-BR-75,IND,SIG	4.260E+07	1.060E+08	J,RCA,30,67,82	ALFASSI+	2GERJUL	41
A0187004	35-BR-79(P,5N)36-KR-75,IND,SIG	4.980E+07	6.430E+07	J,ARI,30,188,79	DE JONG+	2NEDIKO	19
A0253008	33-AS-75(HE3,2N)35-BR-76-G,IND/M+,SIG	9.100E+06	3.701E+07	J,ARI,31,267,80	PAANS+	2NEDGRN	10
A0232002	33-AS-75(HE3,2N)35-BR-76,IND,SIG	1.260E+07	7.094E+07	J,RCA,30,67,82	ALFASSI+	2GERJUL	54
A0160003	33-AS-75(HE3,2N)35-BR-76,IND/M+,SIG	1.465E+07	3.587E+07	C,79INNSBR,,202,80	WEINREICH+	2GERJUL	20
A0253011	33-AS-75(A,3N)35-BR-76-G,IND/M+,SIG	3.793E+07	7.170E+07	J,ARI,31,267,80	PAANS+	2NEDGRN	10
A0232007	33-AS-75(A,3N)35-BR-76,IND,SIG	2.870E+07	1.058E+08	J,RCA,30,67,82	ALFASSI+	2GERJUL	48
A0184008	33-AS-75(A,3N)35-BR-76-G,IND/M+,SIG	3.000E+07	4.000E+07	J,ARI,30,79,79	NOZAKI+	2JPNJCL	3
A0060003	34-SE-77(P,N)35-BR-77-G,IND,SIG	2.800E+06	3.000E+06	J,IZV,41,(8),1603,77	FEDOREC+	4CCPKFT	5
A0073002	34-SE-77(P,N)35-BR-77-M/G,IND,SIG/RAT	3.600E+06	9.000E+06	C,80LENGRD,,324,8003	SKAKUN+	4CCPKFT	5
A0255002	34-SE-77(P,N)35-BR-77-G,IND/M+,SIG	9.900E+06	2.459E+07	J,ARI,31,405,80	JANSSEN+	2NEDENT	16
B0071006	34-SE-77(P,N)35-BR-77,M+,SIG	4.000E+06	4.000E+08	J,JIN,31,1915,69	REULAND+	1USACAR	1
B0066017	34-SE-77(P,N)35-BR-77-M+G,,SIG/SUM	2.190E+06	5.540E+06	P,ORNL-2910,25,60	JOHNSON+	1USAORL	63
B0046011	34-SE-77(P,N)35-BR-77,,SIG	2.170E+06	2.679E+06	J,PR,109,1243,58	JOHNSON+	1USAORL	36
A0255004	34-SE-78(P,2N)35-BR-77-G,IND/M+,SIG	1.368E+07	2.458E+07	J,ARI,31,405,80	JANSSEN+	2NEDENT	13
A0243002	33-AS-75(A,2N)35-BR-77,IND,SIG	1.380E+07	2.810E+07	J,JIN,35,3413,73	WATERS+	2UK UK	13
A0232006	33-AS-75(A,2N)35-BR-77,IND,SIG	2.610E+07	1.255E+08	J,RCA,30,67,82	ALFASSI+	2GERJUL	45
A0184007	33-AS-75(A,2N)35-BR-77-G,IND/M+,SIG	2.000E+07	4.000E+07	J,ARI,30,79,79	NOZAKI+	2JPNJCL	5
A0184002	34-SE-0(P,X)35-BR-77-G,IND/M+,SIG	1.000E+07	5.000E+07	J,ARI,30,79,79	NOZAKI+	2JPNJCL	9
A0187002	35-BR-79(P,3N)36-KR-77,IND,SIG	2.460E+07	6.470E+07	J,ARI,30,188,79	DE JONG+	2NEDIKO	52
B0171012	35-BR-79(P,3N)36-KR-77,,SIG	2.500E+07	8.500E+07	J,PR/C,19,1753,79	DIKSIC+	1CANMCG	15
B0171004	35-BR-81(P,5N)36-KR-77,,SIG	4.500E+07	8.500E+07	J,PR/C,19,1753,79	DIKSIC+	1CANMCG	6
A0154002	34-SE-76(HE3,2N)36-KR-77,IND,SIG	1.315E+07	3.505E+07	J,ARI,33,13,82	HE YOUFENG+	2GERJUL	21
A0154004	34-SE-77(HE3,3N)36-KR-77,IND,SIG	1.486E+07	3.572E+07	J,ARI,33,13,82	HE YOUFENG+	2GERJUL	12
B0171011	35-BR-79(P,N)36-KR-79-G,M+,SIG	1.000E+07	8.500E+07	J,PR/C,19,1753,79	DIKSIC+	1CANMCG	12
B0061009	35-BR-79(P,N)36-KR-79,M+,SIG	6.750E+06	6.750E+06	J,PR,130,1522,63	HUMES+	1USAQSU	1
B0056002	35-BR-79(P,N)36-KR-79,M+,SIG	3.000E+06	2.482E+07	J,PR/C,9,2166,74	COLLE+	1USABNL	23
B0052010	35-BR-79(P,N)36-KR-79,M+,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
B0171003	35-BR-81(P,3N)36-KR-79-G,M+,SIG	2.500E+07	8.500E+07	J,PR/C,19,1753,79	DIKSIC+	1CANMCG	10

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
B0111005	37-RB-85(P,4N+P)37-RB-81-M,IND/UND,SIG	4.660E+07	6.990E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	18
B0111005	37-RB-85(P,4N+P)37-RB-81-G,IND/UND,SIG	4.660E+07	6.990E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	18
B0111005	37-RB-85(P,4N+P)37-RB-81-M+G,IND/UND,SIG/	4.660E+07	6.990E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	18
B0111005	37-RB-85(P,4N+P)37-RB-81-M/G,IND/UND,SIG/	4.660E+07	6.990E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	18
B0111004	37-RB-85(P,5N)38-SR-81,,SIG	4.900E+07	6.990E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	15
B0111003	37-RB-85(P,4N)38-SR-82,,SIG	3.370E+07	6.990E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	21
B0069007	38-SR-88(P,3N+P)38-SR-85-M,UND,SIG	4.200E+07	8.500E+07	J,CJC,45,1149,67	SACHDEV+	1CANMCG	8
B0069007	38-SR-88(P,3N+P)38-SR-85-G,UND,SIG	4.200E+07	8.500E+07	J,CJC,45,1149,67	SACHDEV+	1CANMCG	8
B0130007	40-ZR-90(P,3N+3P)38-SR-85,M+/UND,SIG	3.800E+07	8.600E+07	J,PR/C,14,64,76	KANTELO+	1CANMCG	9
D0029088	37-RB-0(P,X)38-SR-85-M,IND,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
D0029088	37-RB-0(P,X)38-SR-85-G,IND,SIG	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
D0029088	37-RB-0(P,X)38-SR-85-M+G,IND,SIG/SUM	5.930E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	1
D0029011	39-Y-89(P,X)38-SR-85-M,IND,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
D0029011	39-Y-89(P,X)38-SR-85-G,CUM,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
D0029011	39-Y-89(P,X)38-SR-85-M+G,IND,SIG/SUM	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
A0137005	42-MO-0(P,X)38-SR-85,(CUM),SIG	8.000E+08	8.000E+08	C,75WASH,2,492,75	ERDAL+	1USALAS	1
B0026012	92-U-238(P,X)38-SR-85,CUM/(M),SIG	3.000E+11	3.000E+11	J,PR/C,9,1138,74	CHANG+	1USACHI	1
P0033011	38-SR-87(P,N)39-Y-87,,SIG	2.610E+06	6.820E+06	J,HPA,24,441,51	BLASER+	2SWTSWT	13
A0074003	38-SR-87(P,N)39-Y-87-M/G,IND,SIG/RAT	4.000E+06	9.100E+06	C,80LENGRD,,325,8003	SKAKUN+	4CCPKFT	5
B0069003	38-SR-88(P,2N)39-Y-87-M,,SIG	1.500E+07	3.300E+07	J,CJC,45,1149,67	SACHDEV+	1CANMCG	8
B0069003	38-SR-88(P,2N)39-Y-87-G,,SIG	1.500E+07	3.300E+07	J,CJC,45,1149,67	SACHDEV+	1CANMCG	8
B0001003	39-Y-89(P,2N+P)39-Y-87-M,UND,SIG	2.480E+07	8.500E+07	J,PR,144,962,66	SAHA+	1CANMCG	16
B0001003	39-Y-89(P,2N+P)39-Y-87-G,UND,SIG	2.480E+07	8.500E+07	J,PR,144,962,66	SAHA+	1CANMCG	16
B0001003	39-Y-89(P,2N+P)39-Y-87-M+G,UND,SIG/SUM	2.480E+07	8.500E+07	J,PR,144,962,66	SAHA+	1CANMCG	16
B0001003	39-Y-89(P,2N+P)39-Y-87-M/G,UND,SIG/RAT	2.480E+07	8.500E+07	J,PR,144,962,66	SAHA+	1CANMCG	16
P0064009	37-RB-85(A,2N)39-Y-87-M+G,,SIG/SUM	1.380E+07	3.840E+07	J,JPJ,17,1323,62	IWATA	2JPNKTO	20
B0093013	39-Y-89(P,N)40-ZR-89-M+G,,SIG/SUM	7.000E+06	8.100E+06	J,PR,115,925,59	ALBERT	1USALRL	2
B0052012	39-Y-89(P,N)40-ZR-89-M,,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
B0052012	39-Y-89(P,N)40-ZR-89,M+,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
B0024013	39-Y-89(P,N)40-ZR-89,M+,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
P0033012	39-Y-89(P,N)40-ZR-89-G,SIG	3.550E+06	6.730E+06	J,HPA,24,441,51	BLASER+	2SWTSWT	10
P0025002	39-Y-89(P,N)40-ZR-89,,SIG	3.660E+06	5.840E+06	J,NP/A,107,21,68	JOHNSON+	1USAORL	59
P0012003	39-Y-89(P,N)40-ZR-89-M,,SIG	6.680E+06	1.970E+07	J,JET,17,1186,63	GRITSYNA+	4CCPUFT	13
P0012002	39-Y-89(P,N)40-ZR-89-G,,SIG	6.380E+06	1.990E+07	J,JET,17,1186,63	GRITSYNA+	4CCPUFT	12
B0018002	39-Y-89(P,N)40-ZR-89,M+,SIG	3.900E+06	4.420E+07	J,NP/A,201,579,73	BIRATTARI+	2ITYMIL	20
B0001002	39-Y-89(P,N)40-ZR-89,M+,SIG	5.000E+06	8.500E+07	J,PR,144,962,66	SAHA+	1CANMCG	19
A0105002	39-Y-89(P,N)40-ZR-89-G/M,,SIG/RAT,,REL	4.800E+06	8.700E+06	C,81SAMAR,346,81	SKAKUN+	4CCPKFT	5
D0029002	39-Y-89(P,N)40-ZR-89,IND,SIG	5.400E+08	5.930E+08	W,GRUETTER,8202	GRUETTER	2SWTWUR	2
A0041003	40-ZR-90(P,X)40-ZR-89-G,CUM,SIG	1.000E+09	1.000E+09	J,IZV,42,(11),2392,78	BELJAEV+	4CCPFTI	12
A0041003	40-ZR-91(P,X)40-ZR-89-G,CUM,SIG	1.000E+09	1.000E+09	J,IZV,42,(11),2392,78	BELJAEV+	4CCPFTI	12
A0041003	40-ZR-94(P,X)40-ZR-89-G,CUM,SIG	1.000E+09	1.000E+09	J,IZV,42,(11),2392,78	BELJAEV+	4CCPFTI	12
P0126009	40-ZR-90(A,A+N)40-ZR-89-G,M+,SIG	2.750E+07	7.810E+07	J,PR,170,1131,68	-WEN,YU+	1USAROC	39
P0126004	40-ZR-90(A,A+N)40-ZR-89-G,M+,SIG	5.450E+07	7.950E+07	J,PR,170,1131,68	-WEN,YU+	1USAROC	12

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
A0164002	42-MO-95(P,N)43-TC-95,,SIG	6.000E+06	9.000E+06	J,YF,36,299,82	TRUFANOV+	4CCPFEI	4
B0025003	42-MO-96(P,2N)43-TC-95-M,,SIG	1.500E+07	8.000E+07	J,PR/C,6,810,72	HOGAN	1CANMCG	10
B0025003	42-MO-96(P,2N)43-TC-95-G,,SIG	1.500E+07	8.000E+07	J,PR/C,6,810,72	HOGAN	1CANMCG	10
B0025003	42-MO-96(P,2N)43-TC-95-M+G,,SIG/SUM	1.500E+07	8.000E+07	J,PR/C,6,810,72	HOGAN	1CANMCG	10
B0109010	42-MO-94(D,N)43-TC-95-M,,SIG	3.400E+06	4.900E+06	J,JIN,38,2289,76	RANDA+	3CSRUJV	2
B0109009	42-MO-94(D,N)43-TC-95-G,,SIG	0.000E+00	4.900E+06	J,JIN,38,2289,76	RANDA+	3CSRUJV	6
A0003002	42-MO-94(D,N)43-TC-95-G,,SIG	5.100E+06	1.180E+07	J,IZV,39,2127,75	ALEKSANDROV+	4CCPSUL	16
B0109006	42-MO-0(D,X)43-TC-95-M,,SIG,,FCT	0.000E+00	1.270E+07	J,JIN,38,2289,76	RANDA+	3CSRUJV	22
B0109006	42-MO-0(D,X)43-TC-95-G,,SIG,,FCT	0.000E+00	1.270E+07	J,JIN,38,2289,76	RANDA+	3CSRUJV	22
B0109006	42-MO-0(D,X)43-TC-95-M/G,,SIG/RAT	0.000E+00	1.270E+07	J,JIN,38,2289,76	RANDA+	3CSRUJV	22
P0111009	41-NB-93(A,2N)43-TC-95-M,,SIG	1.900E+07	4.190E+07	J,PR,139,886,65	MATSUO+	1USACLK	15
P0111008	41-NB-93(A,2N)43-TC-95-G,,SIG	1.910E+07	4.210E+07	J,PR,139,886,65	MATSUO+	1USACLK	14
B0040007	42-MO-92(A,P)43-TC-95-M,,SIG	1.200E+07	3.150E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	17
B0040007	42-MO-92(A,P)43-TC-95-G,,SIG	1.200E+07	3.150E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	17
B0040011	42-MO-94(A,2N+P)43-TC-95-M,UND,SIG	2.980E+07	5.600E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	14
B0040011	42-MO-94(A,2N+P)43-TC-95-G,UND,SIG	2.980E+07	5.600E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	14
B0025002	42-MO-96(P,N)43-TC-96-M,,SIG	1.000E+07	8.000E+07	J,PR/C,6,810,72	HOGAN	1CANMCG	11
B0025002	42-MO-96(P,N)43-TC-96-G,,SIG	1.000E+07	8.000E+07	J,PR/C,6,810,72	HOGAN	1CANMCG	11
B0025002	42-MO-96(P,N)43-TC-96-M+G,,SIG/SUM	1.000E+07	8.000E+07	J,PR/C,6,810,72	HOGAN	1CANMCG	11
B0109011	42-MO-95(D,N)43-TC-96,M+,SIG	0.000E+00	5.200E+06	J,JIN,38,2289,76	RANDA+	3CSRUJV	6
B0109007	42-MO-0(D,X)43-TC-96,M+,SIG,,FCT	0.000E+00	1.270E+07	J,JIN,38,2289,76	RANDA+	3CSRUJV	21
P0111007	41-NB-93(A,N)43-TC-96-G,,SIG	1.310E+07	2.620E+07	J,PR,139,886,65	MATSUO+	1USACLK	16
P0111006	41-NB-93(A,N)43-TC-96-M,,SIG	1.360E+07	2.650E+07	J,PR,139,886,65	MATSUO+	1USACLK	16
P0070014	41-NB-93(A,N)43-TC-96-M+G,,SIG/SUM	8.600E+06	1.100E+07	J,PR/B,133,911,64	STELSON+	1USAORL	13
B0040012	42-MO-94(A,N+P)43-TC-96,M+/UND,SIG	2.060E+07	5.900E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	12
B0040014	42-MO-95(A,2N+P)43-TC-96,M+/UND,SIG	2.790E+07	6.000E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	11
B0040004	42-MO-92(A,2N)44-RU-94,,SIG	1.900E+07	4.100E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	17
B0040002	42-MO-92(A,N)44-RU-95,,SIG	1.200E+07	3.000E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	12
B0040010	42-MO-94(A,N)44-RU-97,,SIG	1.200E+07	5.900E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	17
B0040013	42-MO-95(A,2N)44-RU-97,,SIG	1.840E+07	6.000E+07	J,JIN,36,3647,74	GRAF+	2GERKFK	15
P0033018	44-RU-101(P,N)45-RH-101-M,,SIG	2.920E+06	6.190E+06	J,HPA,24,441,51	BLASER+	2SWTSWT	10
B0052015	44-RU-101(P,N)45-RH-101-M,,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
B0026017	92-U-238(P,X)46-PD-100,CUM,SIG	3.000E+11	3.000E+11	J,PR/C,9,1138,74	CHANG+	1USACHI	1

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
B0065006	47-AG-107(P,N)48-CD-107,,SIG	1.900E+06	1.050E+07	J,PR,128,280,62	WING+	1USAANL	24
B0057004	47-AG-107(P,N)48-CD-107,,SIG	2.510E+06	2.340E+07	J,PR/C,9,1819,74	COLLE+	1USABNL	46
B0048007	47-AG-107(P,N)48-CD-107,,SIG	3.310E+06	6.400E+06	J,HPA,24,3,51	BLASER+	2SWTETH	18
B0048010	48-CD-111(P,N)49-IN-111,M+,SIG	3.040E+06	6.400E+06	J,HPA,24,3,51	BLASER+	2SWTETH	18
A0135002	48-CD-111(P,N)49-IN-111-M,,SIG	6.100E+06	9.100E+06	C,79RIGA,,290,79	SKAKUN+	4CCPKFT	3
A0135002	48-CD-111(P,N)49-IN-111-G+M,,SIG/SUM	6.100E+06	9.100E+06	C,79RIGA,,290,79	SKAKUN+	4CCPKFT	3
A0135002	48-CD-111(P,N)49-IN-111-M/G,,SIG/RAT	6.100E+06	9.100E+06	C,79RIGA,,290,79	SKAKUN+	4CCPKFT	3
P0019006	48-CD-111(P,N)49-IN-111-G,,SIG	4.300E+06	1.470E+07	J,NP,80,335,66	OTOZAI+	2JPNOSA	4
B0068032	48-CD-111(P,N)49-IN-111-M+G,,SIG/SUM	2.490E+06	5.670E+06	P,ORNL-2910,25,80	JOHNSON+	1USAORL	18
B0065008	48-CD-111(P,N)49-IN-111,M+,SIG	2.100E+06	1.010E+07	J,PR,128,280,62	WING+	1USAANL	10
B0052016	48-CD-111(P,N)49-IN-111,M+,SIG	1.200E+07	1.200E+07	J,PR,100,1340,55	BLOSSER+	1USAORL	1
A0001004	48-CD-111(P,N)49-IN-111,M+,SIG	4.300E+06	2.090E+07	J,IZV,39,24,75	SKAKUN+	4CCPUFT	16
P0019011	48-CD-112(P,2N)49-IN-111-G,,SIG	9.400E+06	3.740E+07	J,NP,80,335,66	OTOZAI+	2JPNOSA	12
A0001007	48-CD-112(P,2N)49-IN-111,M+,SIG	1.320E+07	2.090E+07	J,IZV,39,24,75	SKAKUN+	4CCPUFT	6
P0094002	47-AG-109(A,2N)49-IN-111,,SIG	1.450E+07	1.840E+07	J,PR,90,460,53	BLEULER+	1USAPUR	8
A0206003	47-AG-109(A,2N)49-IN-111-M/G,,SIG/RAT	1.700E+07	3.200E+07	J,IZV,48,38,84	BASKOVA+	4CCPMOS	9
D0051007	47-AG-109(A,2N)49-IN-111,,SIG	2.040E+07	5.390E+07	W,NASSIFF,840110	WASILEVSKY+	3ARGCNE	13
A0067004	47-AG-109(A,2N)49-IN-111-G/M,,SIG/RAT	1.700E+07	2.900E+07	J,IZV,44,155,80	AVCHUKHOV+	4CCPMOS	7
B0014023	92-U-238(P,F)50-SN-117-M,IND,SIG	4.500E+08	4.500E+08	J,JIN,34,1485,72	PANONTIN+	1USACHI	1
A0217003	50-SN-116(A,2N)52-TE-118,,SIG	1.970E+07	2.970E+07	C,84ALMAAT,,355,8404	BATIJ+	4CCPMOS	9
B0081005	53-I-127(P,6N)54-XE-122,,SIG	5.500E+07	8.500E+07	J,JIN,39,1299,77	DIKSIC+	1CANMCG	6
R0005002	53-I-127(P,6N)54-XE-122,IND,SIG	6.600E+08	6.600E+08	J,ARI,31,163,80	ADILBISH+	4CCPJIA	1
A0062002	53-I-127(P,6N)54-XE-122,,SIG	6.600E+08	6.600E+08	R,JINR-P6-12447,79	ADILBISH+	4ZZZDUB	1
B0143005	53-I-127(D,7N)54-XE-122,,SIG	6.250E+07	8.900E+07	J,ARI,25,535,74	WEINREICH+	2GERJUL	15
A0266008	52-TE-124(P,2N)53-I-123,IND,SIG	1.233E+07	2.927E+07	J,ARI,26,741,75	ACERBI+	2ITYMIL	7
B0090003	52-TE-124(P,2N)53-I-123,,SIG,,FCT	1.220E+07	2.918E+07	J,ARI,28,395,77	KONDO+	1USABNL	28
B0071009	52-TE-124(P,2N)53-I-123,,SIG	4.000E+08	4.000E+08	J,JIN,31,1915,69	REULAND+	1USACAR	1
A0234009	52-TE-122(D,N)53-I-123,IND,SIG	7.460E+06	3.395E+07	J,ARI,34,1425,83	ZAIDI+	2GERJUL	33
A0238003	51-SB-121(HE3,N)53-I-123,IND,SIG	1.240E+07	2.580E+07	J,JIN,35,3047,73	WATSON+	2UK UK	10
A0238003	51-SB-123(HE3,3N)53-I-123,IND,SIG	1.240E+07	2.580E+07	J,JIN,35,3047,73	WATSON+	2UK UK	10
A0238002	51-SB-0(A,X)53-I-123,IND,SIG	9.720E+06	2.820E+07	J,JIN,35,3047,73	WATSON+	2UK UK	20
A0238002	51-SB-121(A,2N)53-I-123,IND,SIG	9.720E+06	2.820E+07	J,JIN,35,3047,73	WATSON+	2UK UK	20
R0004003	51-SB-121(A,2N)53-I-123,IND,SIG	1.457E+07	2.651E+07	J,NP/A,383,251,82	CALBOREANU+	3RUMBUC	37
D0030005	51-SB-121(A,2N)53-I-123,,SIG	1.457E+07	2.651E+07	W,CALBOREANU,811225	CALBOREANU+	3RUMBUC	37

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
A0266009	52-TE-124(P,N)53-I-124,IN.,SIG	9.580E+06	2.929E+07	J,ARI,26,741,75	ACERBI+	2ITYMIL	8
B0090002	52-TE-124(P,N)53-I-124,,S G,,FCT	9.950E+06	2.918E+07	J,ARI,28,395,77	KONDO+	1USABNL	29
B0071008	52-TE-124(P,N)53-I-124,,S,G	4.000E+08	4.000E+08	J,JIN,31,1915,69	REULAND+	1USACAR	1
B0024023	52-TE-125(P,2N)53-I-124,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
B0024027	52-TE-126(P,3N)53-I-124,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
B0081007	53-I-127(P,3N+P)53-I-124,UND,SIG	3.000E+07	8.500E+07	J,JIN,39,1299,77	DIKSIC+	1CANMCG	12
A0266003	52-TE-0(P,X)53-I-124,IND,SIG	1.175E+07	3.397E+07	J,ARI,26,741,75	ACERBI+	2ITYMIL	9
B0143010	53-I-127(D,4N+P)53-I-124,UND,SIG	4.560E+07	8.930E+07	J,ARI,25,535,74	WEINREICH+	2GERJUL	23
A0234008	52-TE-0(D,X)53-I-124,IND,SIG	7.610E+06	1.333E+07	J,ARI,34,1425,83	ZAIDI+	2GERJUL	9
A0234007	52-TE-0(D,X)53-I-124,IND,SIG	6.860E+06	1.343E+07	J,ARI,34,1425,83	ZAIDI+	2GERJUL	10
A0238003	51-SB-0(HE3,X)53-I-124,IND,SIG	1.240E+07	2.580E+07	J,JIN,35,3047,73	WATSON+	2UK UK	10
A0238003	51-SB-123(HE3,2N)53-I-124,IND,SIG	1.240E+07	2.580E+07	J,JIN,35,3047,73	WATSON+	2UK UK	10
R0004002	51-SB-121(A,N)53-I-124,IND,SIG	1.150E+07	2.651E+07	J,NP/A,383,251,82	CALBOREANU+	3RUMBUC	34
D0030004	51-SB-121(A,N)53-I-124,,SIG	1.150E+07	2.651E+07	W,CALBOREANU,811225	CALBOREANU+	3RUMBUC	34
A0238002	51-SB-0(A,X)53-I-124,IND,SIG	9.720E+06	2.820E+07	J,JIN,35,3047,73	WATSON+	2UK UK	20
A0238002	51-SB-121(A,N)53-I-124,IND,SIG	9.720E+06	2.820E+07	J,JIN,35,3047,73	WATSON+	2UK UK	20
A0238002	51-SB-123(A,3N)53-I-124,IND,SIG	9.720E+06	2.820E+07	J,JIN,35,3047,73	WATSON+	2UK UK	20
R0007002	53-I-127(P,5N)54-XE-123,IND,SIG	2.080E+07	1.585E+08	J,ARI,29,29,73	SYME+	2UK HAR	26
R0005002	53-I-127(P,5N)54-XE-123,IND,SIG	6.600E+08	6.600E+08	J,ARI,31,163,80	ADILBISH+	4CCPJIA	1
R0002002	53-I-127(P,5N)54-XE-123,IND,SIG	4.640E+07	7.560E+07	J,ARI,27,465,76	PAANS+	2NEDGRN	8
A0265002	53-I-127(P,5N)54-XE-123,IND,SIG	4.524E+07	6.235E+07	J,ARI,26,279,75	WILKINS+	1USADAV	8
R0024002	53-I-127(P,5N)54-XE-123,IND,SIG	4.540E+07	6.240E+07	J,ARI,26,279,75	WILKINS+	1USADAV	8
B0148002	53-I-127(P,5N)54-XE-123,,SIG	3.810E+07	1.591E+08	J,ARI,29,29,78	SYME+	2UK HAR	19
B0081004	53-I-127(P,5N)54-XE-123,,SIG	4.500E+07	8.500E+07	J,JIN,39,1299,77	DIKSIC+	1CANMCG	8
A0062002	53-I-127(P,5N)54-XE-123,,SIG	6.600E+08	6.600E+08	R,JINR-P6-12447,79	ADILBISH+	4ZZZDUB	1
A0161002	53-I-127(P,5N)54-XE-123,IND,SIG	4.635E+07	6.548E+07	J,ARI,27,465,76	PAANS+	2NEDGRN	8
B0143004	53-I-127(D,6N)54-XE-123,,SIG	4.560E+07	8.670E+07	J,ARI,25,535,74	WEINREICH+	2GERJUL	21
R0007002	53-I-127(P,3N)54-XE-125,IND,SIG	2.080E+07	1.585E+08	J,ARI,29,29,73	SYME+	2UK HAR	26
R0005002	53-I-127(P,3N)54-XE-125,IND/M+,SIG	6.600E+08	6.600E+08	J,ARI,31,163,80	ADILBISH+	4CCPJIA	1
R0002002	53-I-127(P,3N)54-XE-125,IND/M+,SIG	4.640E+07	7.560E+07	J,ARI,27,465,76	PAANS+	2NEDGRN	8
A0062002	53-I-127(P,3N)54-XE-125,,SIG	6.600E+08	6.600E+08	R,JINR-P6-12447,79	ADILBISH+	4ZZZDUB	1
A0265003	53-I-127(P,3N)54-XE-125,IND,SIG	4.515E+07	6.236E+07	J,ARI,26,279,75	WILKINS+	1USADAV	8
R0024003	53-I-127(P,3N)54-XE-125,IND/M+,SIG	4.530E+07	6.240E+07	J,ARI,26,279,75	WILKINS+	1USADAV	8
B0148003	53-I-127(P,3N)54-XE-125,M+,SIG	2.130E+07	1.590E+08	J,ARI,29,29,78	SYME+	2UK HAR	11
B0081003	53-I-127(P,3N)54-XE-125,M+,SIG	2.000E+07	8.500E+07	J,JIN,39,1299,77	DIKSIC+	1CANMCG	11
A0161003	53-I-127(P,3N)54-XE-125,IND,SIG	4.635E+07	6.548E+07	J,ARI,27,465,76	PAANS+	2NEDGRN	8
B0143003	53-I-127(D,4N)54-XE-125,M+,SIG	2.420E+07	8.920E+07	J,ARI,25,535,74	WEINREICH+	2GERJUL	28

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
B0081002	53-I-127(P,N)54-XE-127,M+,SIG	2.000E+07	8.500E+07	J,JIN,39,1299,77	DIKSIC+	1CANMCG	10
B0056003	53-I-127(P,N)54-XE-127,M+,SIG	3.010E+06	2.482E+07	J,PR/C,9,2166,74	COLLE+	1USABNL	26
A0137003	57-LA-139(P,5N+2A)54-XE-127,CUM/UND,SIG	5.900E+08	8.000E+08	C,75WASH,2,492,75	ERDAL+	1USALAS	2
B0012020	92-U-238(P,F)54-XE-127,IND,SIG	1.150E+10	1.150E+10	J,PR/C,8,1091,73	YU+	1USAPUR	1
B0012006	92-U-238(P,F)54-XE-127,CUM,SIG	1.150E+10	1.150E+10	J,PR/C,8,1091,73	YU+	1USAPUR	1
B0143002	53-I-127(D,2N)54-XE-127,M+,SIG	6.500E+06	8.930E+07	J,ARI,25,535,74	WEINREICH+	2GERJUL	33
R0001002	55-CS-133(P,X)54-XE-127,CUM,SIG	5.400E+08	5.400E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	6
B0180002	55-CS-133(P,X)54-XE-127-G,CUM,SIG	3.560E+08	5.880E+08	J,ARI,30,631,79	PEEK+	1USACLA	7
B0180002	55-CS-133(P,X)54-XE-127-G,IND/M+,SIG	3.560E+08	5.880E+08	J,ARI,30,631,79	PEEK+	1USACLA	7
R0001014	55-CS-133(P,X)54-XE-127,CUM,SIG	3.510E+08	5.880E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	6
R0001004	55-CS-133(P,X)54-XE-127,IND/M+,SIG	5.400E+08	5.400E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	2
R0001006	56-BA-0(P,X)54-XE-127,CUM,SIG	5.400E+08	5.400E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	6
B0180006	56-BA-0(P,X)54-XE-127-G,CUM,SIG	3.680E+08	5.900E+08	J,ARI,30,631,79	PEEK+	1USACLA	7
B0180006	56-BA-0(P,X)54-XE-127-G,IND/M+,SIG	3.680E+08	5.900E+08	J,ARI,30,631,79	PEEK+	1USACLA	7
R0001015	56-BA-0(P,X)54-XE-127,CUM,SIG	3.670E+08	5.890E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	6
R0001008	56-BA-0(P,X)54-XE-127,IND/M+,SIG	5.400E+08	5.400E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	2
R0001010	57-LA-139(P,X)54-XE-127,CUM,SIG	5.400E+08	5.400E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	6
B0180010	57-LA-139(P,X)54-XE-127-G,CUM,SIG	3.170E+08	5.890E+08	J,ARI,30,631,79	PEEK+	1USACLA	7
B0180010	57-LA-139(P,X)54-XE-127-G,IND/M+,SIG	3.170E+08	5.890E+08	J,ARI,30,631,79	PEEK+	1USACLA	7
R0001016	57-LA-139(P,X)54-XE-127,CUM,SIG	3.120E+08	5.910E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	7
R0001012	57-LA-139(P,X)54-XE-127,IND/M+,SIG	5.400E+08	5.400E+08	J,ARI,30,631,79	PEEK+	2SWTVIL	2
B0012022	92-U-238(P,F)54-XE-129,IND,SIG	1.150E+10	1.150E+10	J,PR/C,8,1091,73	YU+	1USAPUR	1
B0012008	92-U-238(P,F)54-XE-129,CUM,SIG	1.150E+10	1.150E+10	J,PR/C,8,1091,73	YU+	1USAPUR	1
P0127003	65-TB-159(D,4N)66-DY-157,,SIG	1.970E+07	2.680E+07	J,CR,266,100,68	M.DUC+	2FR LYO	9
B0018004	69-TM-169(P,N)70-YB-169,M+,SIG	3.300E+06	4.390E+07	J,NP/A,201,579,73	BIRATTARI+	2ITYMIL	20
B0038005	73-TA-181(P,4N)74-W-178,,SIG	2.800E+07	4.420E+07	J,NP/A,166,605,71	BIRATTARI+	2ITYMIL	8
P0115007	74-W-186(D,2N)75-RE-186,,SIG	5.940E+06	1.400E+07	J,NP,86,429,66	PEMENT+	1USAPUP	9
S0014003	74-W-186(D,2N)75-RE-186,,SIG	7.000E+06	1.570E+07	J,CNP,3,(3),242,8108	TAO ZHENLAN+	3CPRNRS	10
A0202004	74-W-186(D,2N)75-RE-186,IND,SIG	7.300E+06	1.670E+07	J,RCA,19,(3),97,73	NASSIFF+	2GERKFK	6

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
B0024030	80-HG-202(P,2N)81-TL-201,,SIG	4.000E+08	4.000E+08	J,PR,178,1732,69	CHURCH+	1USACAR	1
B0168003	81-TL-0(P,X)82-PB-201-G,M+,PY,,FCT	1.720E+07	5.900E+07	J,ARI,29,159,78	LAGUNAS-SOLA	1USADAV	78
B0168003	81-TL-203(P,3N)82-PB-201-G,M+,SIG	1.720E+07	5.900E+07	J,ARI,29,159,78	LAGUNAS-SOLA	1USADAV	78
B0168003	81-TL-205(P,5N)82-PB-201-G,M+,SIG	1.720E+07	5.900E+07	J,ARI,29,159,78	LAGUNAS-SOLA	1USADAV	78
A0180002	81-TL-205(P,5N)82-PB-201,IND,SIG	3.400E+07	5.870E+07	J,ARI,31,117,80	LAGUNAS-SOLA	1USADAV	24
P0013003	81-TL-0(P,X)82-PB-201-G,,SIG	1.040E+07	5.170E+07	J,NP,65,177,85	SAKAI+	2JPNTOK	6
A0185005	81-TL-0(P,X)82-PB-201,IND,SIG	1.720E+07	4.410E+07	J,ARI,30,85,79	QAIM+	2GERJUL	25
B0168005	81-TL-205(P,3N)82-PB-203-G,M+,SIG	1.700E+07	5.910E+07	J,ARI,29,159,78	LAGUNAS-SOLA	1USADAV	45
A0180006	81-TL-205(P,3N)82-PB-203,IND,SIG	3.630E+07	5.880E+07	J,ARI,31,117,80	LAGUNAS-SOLA	1USADAV	13
P0013004	81-TL-0(P,X)82-PB-203-G,,SIG	1.000E+07	5.150E+07	J,NP,65,177,85	SAKAI+	2JPNTOK	6
A0185003	81-TL-0(P,X)82-PB-203,IND/M+,SIG	7.490E+06	4.440E+07	J,ARI,30,85,79	QAIM+	2GERJUL	30
B0035004	83-BI-209(P,3N+P)83-BI-206,UND,SIG	3.070E+07	5.160E+07	J,NP/A,230,98,74	MIYANO+	2JPNNII	13
D0045004	82-PB-0(A,XN)84-PO-206,,SIG,,AV	2.100E+07	5.500E+07	J,RRL,50,(4),211,82	WASILEVSKY+	3ARGCNE	17
A0246002	83-BI-209(A,2N)85-AT-211,IND,SIG	2.060E+07	4.330E+07	J,PR,114,154,59	RAMLER+	1USAANL	22

Thick Target Yield (TTY) EXFOR INDEX

for Medical Radioisotopes Production

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
A0195003	5-B-11(P,N)6-C-11,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168005	5-B-11(P,N)6-C-11,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0195154	7-N-14(P,A)6-C-11,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0174004	5-B-10(D,N)6-C-11,PAR,TTY,G	9.700E+04	1.700E+05	J,NP/A,376,379,82	CECIL+	1USACSM	7
A0144002	6-C-12(P,G)7-N-13,,TTY	4.070E+05	1.996E+06	J,PR,84,1219,511215	SEAGRAVE	1USACAL	31
A0195004	6-C-13(P,N)7-N-13,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168008	6-C-13(P,N)7-N-13,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0195155	8-O-16(P,A)7-N-13,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
D0048005	6-C-12(A,N)8-O-15,,TTY,,,DERIV	3.700E+06	9.900E+06	R,AERE-R-10502,8206	WEST+	2UK HAR	63
D0047005	6-C-12(A,N)8-O-15,,TTY	3.611E+06	9.961E+06	R,AERE-R-10502,8206	WEST+	2UK HAR	26
A0195005	8-O-18(P,N)9-F-18,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168011	8-O-18(P,N)9-F-18,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194012	9-F-19(D,X)9-F-18,CUM,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0194012	9-F-19(D,T)9-F-18,IND,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0194012	9-F-19(D,3N)10-NE-18,IND,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
B0176002	10-NE-20(D,A)9-F-18,,TTY	1.650E+07	1.650E+07	J,ARI,29,175,78	LAMBRECHT+	1USABNL	1
B0151002	8-O-16(HE3,P)9-F-18,CUM,TTY	7.700E+06	4.030E+07	J,ARI,28,781,77	FITSCHEN+	2GERHAM	19
A0183002	8-O-16(A,D)9-F-18,CUM/UND,TTY,,RAW	5.500E+07	5.500E+07	J,ARI,30,61,79	BAKKER+	2NEDIKO	1
A0188007	9-F-19(A,N)11-NA-22,,TTY,,,EVAL	2.600E+06	8.000E+06	J,VAT/O,,(4),31,83	VUKOLOV+	4CCPKUR	31
D2001040	9-F-19(A,N)11-NA-22,,TTY	4.000E+06	5.500E+06	J,ANE,10,(10),541,8302	JACOBS+	2ZZZGEL	4
B0174008	13-AL-27(A,3P)12-MG-28,,TTY	2.940E+07	1.600E+08	J,ARI,27,431,76	PROBST+	2GERJUL	87
A0053003	13-AL-27(A,3P)12-MG-28,IND,TTY	3.800E+07	4.500E+07	J,AE,46,185,79	DMITRIEV+	4CCPFEI	8
D0047010	13-AL-27(A,N)15-P-30,,TTY	3.611E+06	9.955E+06	R,AERE-R-10502,8206	WEST+	2UK HAR	25
D2001009	13-AL-27(A,N)15-P-30,,TTY/DA/DE	4.000E+06	5.500E+06	J,ANE,10,(10),541,8302	JACOBS+	2ZZZGEL	1648
D2001008	13-AL-27(A,N)15-P-30,,TTY/DE	4.000E+06	5.500E+06	J,ANE,10,(10),541,8302	JACOBS+	2ZZZGEL	75
D2001006	13-AL-27(A,N)15-P-30,,TTY	4.000E+06	5.500E+06	J,ANE,10,(10),541,8302	JACOBS+	2ZZZGEL	4
D0048009	13-AL-27(A,N)15-P-30,,TTY,,,DERIV	3.700E+06	9.900E+06	R,AERE-R-10502,8206	WEST+	2UK HAR	63
A0195168	20-CA-48(P,X)20-CA-47,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168020	20-CA-0(P,X)20-CA-47,CUM,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194022	20-CA-0(D,X)20-CA-47,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
A0195062	21-SC-45(P,2N)22-TI-44,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168028	21-SC-45(P,2N)22-TI-44,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0021002	21-SC-45(P,2N)22-TI-44,IND,TTY	1.450E+07	2.230E+07	J,AE,34,404,7305	DMITRIEV+	4CCPFEI	6
A0194032	21-SC-45(D,3N)22-TI-44,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0021003	21-SC-45(D,3N)22-TI-44,IND,TTY	1.700E+07	2.260E+07	J,AE,34,404,7305	DMITRIEV+	4CCPFEI	6
A0195009	21-SC-45(P,N)22-TI-45,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0194033	21-SC-45(D,2N)22-TI-45,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0195011	23-V-51(P,N)24-CR-51,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168032	23-V-51(P,N)24-CR-51,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0195012	24-CR-52(P,N)25-MN-52,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195063	26-FE-56(P,2N)27-CO-55,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168040	26-FE-56(P,2N)27-CO-55,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
B0178002	25-MN-55(HE3,3N)27-CO-55,,TTY	1.450E+07	3.950E+07	J,ARI,30,625,79	WATANABE+	2JPNTOK	39
B0160002	26-FE-0(HE3,X)27-CO-55,,TTY	2.500E+07	2.500E+07	J,ARI,28,561,77	NEIRINCKX	3SAFNLP	5
B0128002	28-NI-0(A,X)29-CU-61,CUM,TTY	8.300E+06	3.830E+07	J,ARI,29,611,78	MURAMATSU+	2JPNTOK	21
A0195166	30-ZN-68(P,2P)29-CU-67,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168053	30-ZN-0(P,X)29-CU-67,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194067	30-ZN-0(D,X)29-CU-67,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
B0161002	30-ZN-64(D,2P)29-CU-64,,TTY,,(A)	1.600E+07	1.600E+07	J,ARI,28,802,77	NEIRINCKX	3SAFNLP	2
B0161002	30-ZN-0(D,X)29-CU-67,,TTY,,(A)	1.600E+07	1.600E+07	J,ARI,28,802,77	NEIRINCKX	3SAFNLP	2

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A0195064	29-CU-63(P,2N)30-ZN-62,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168054	29-CU-63(P,2N)30-ZN-62,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194068	29-CU-63(D,3N)30-ZN-62,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
B0164002	28-NI-60(A,2N)30-ZN-62,,TTY,,A	1.280E+07	3.190E+07	J,ARI,28,808,77	NEIRINCKX	3SAFNLP	19
A0287007	30-ZN-66(P,N)31-GA-66,,TTY	1.040E+07	1.040E+07	J,JRN,82,135,84	ISSHIKI+	2JPNTOH	1
A0195018	30-ZN-66(P,N)31-GA-66,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168058	30-ZN-0(P,X)31-GA-66,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194072	30-ZN-0(D,X)31-GA-66,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
B0135004	30-ZN-0(A,X)31-GA-66,,TTY	2.000E+07	3.820E+07	J,ARI,29,615,78	NAGAME+	2JPNTOK	21
A0195065	30-ZN-68(P,2N)31-GA-67,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
B0135003	30-ZN-0(A,X)31-GA-67,,TTY	1.270E+07	3.600E+07	J,ARI,29,615,78	NAGAME+	2JPNTOK	22
B0097002	30-ZN-0(A,X)31-GA-67,CUM,TTY	8.800E+06	9.650E+07	R,CSIR-FIS-91,76	HAASBROEK+	3SAFNLP	13
A0195066	31-GA-69(P,2N)32-GE-68,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168061	31-GA-69(P,2N)32-GE-68,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194075	31-GA-69(D,3N)32-GE-68,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0006009	31-GA-71(A,N)33-AS-74,,TTY,,A	1.300E+07	4.410E+07	J,AE,41,48,76	DMITRIEV+	4CCPFEI	5
A0022004	32-GE-70(A,2N)34-SE-72,,TTY,,A	1.500E+07	4.400E+07	J,AE,34,405,7305	DMITRIEV+	4CCPFEI	6
A0006004	32-GE-0(A,X)34-SE-73,,TTY	1.080E+07	4.400E+07	J,AE,41,48,76	DMITRIEV+	4CCPFEI	5
A0287010	33-AS-75(P,N)34-SE-75,,TTY	1.040E+07	1.040E+07	J,JRN,82,135,84	ISSHIKI+	2JPNTOH	1
A0195023	33-AS-75(P,N)34-SE-75,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168071	33-AS-75(P,N)34-SE-75,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0022002	33-AS-75(P,N)34-SE-75,IND,TTY	6.500E+06	2.180E+07	J,AE,34,405,7305	DMITRIEV+	4CCPFEI	5
A0194084	33-AS-75(D,2N)34-SE-75,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0022003	33-AS-75(D,2N)34-SE-75,IND,TTY	9.100E+06	2.300E+07	J,AE,34,405,7305	DMITRIEV+	4CCPFEI	6
A0168072	34-SE-0(P,X)34-SE-75,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194085	34-SE-0(D,X)34-SE-75,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0022004	32-GE-0(A,X)34-SE-75,,TTY	1.500E+07	4.400E+07	J,AE,34,405,7305	DMITRIEV+	4CCPFEI	6
A0022004	32-GE-70(A,2N)34-SE-72,,TTY,,A	1.500E+07	4.400E+07	J,AE,34,405,7305	DMITRIEV+	4CCPFEI	6
A0184008	33-AS-75(A,3N)35-BR-76-G,IND/M+,TTY	3.000E+07	4.000E+07	J,ARI,30,79,79	NOZAKI+	2JPNJCL	3
A0122005	33-AS-75(A,3N)35-BR-76,,TTY	2.230E+07	4.380E+07	J,AE,52,(1),72,82	DMITRIEV+	4CCPFEI	6

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A0184007	33-AS-75(A,2N)35-BR-77-G,IND/M+,TTY	2.000E+07	4.000E+07	J,ARI,30,79,79	NOZAKI+	2JPNJCL	5
A0122005	33-AS-75(A,2N)35-BR-77,,TTY	2.230E+07	4.380E+07	J,AE,52,(1),72,82	DMITRIEV+	4CCPFEI	6
A0168074	34-SE-0(P,X)35-BR-77-G,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0184002	34-SE-0(P,X)35-BR-77-G,IND/M+,TTY	1.000E+07	5.000E+07	J,ARI,30,79,79	NOZAKI+	2JPNJCL	9
A0195025	35-BR-79(P,N)36-KR-79,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
B0111014	37-RB-85(P,4N+P)37-RB-81-G,IND/UND,TTY	4.590E+07	7.050E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	7
B0111013	37-RB-85(P,4N+P)37-RB-81-M,IND/UND,TTY	4.530E+07	7.050E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	7
B0111012	37-RB-85(P,5N)38-SR-81,,TTY	4.860E+07	7.070E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	9
B0111011	37-RB-85(P,4N)38-SR-82,,TTY	3.700E+07	7.080E+07	J,ARI,31,141,80	HORIGUCHI+	2JPNHIR	11
A0195026	37-RB-85(P,N)38-SR-85,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0194092	37-RB-85(D,2N)38-SR-85,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0168080	37-RB-0(P,X)38-SR-85-G,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0168081	38-SR-0(P,X)38-SR-85-G,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0195070	38-SR-88(P,2N)39-Y-87,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195069	38-SR-88(P,2N)39-Y-87-M,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195028	39-Y-89(P,N)40-ZR-89,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168088	39-Y-89(P,N)40-ZR-89-G,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0085014	39-Y-89(P,N)40-ZR-89-M,,TTY	8.000E+06	1.200E+07	J,AE,49,(2),101,8008	MUMINOV+	4CCPUZB	5
A0194101	39-Y-89(D,2N)40-ZR-89,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0195137	40-ZR-90(P,X)40-ZR-89,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0287014	42-MO-95(P,N)43-TC-95,,TTY	1.040E+07	1.040E+07	J,JRN,82,135,84	ISSHIKI+	2JPNTOH	1
A0168096	42-MO-0(P,X)43-TC-95-M,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0009002	42-MO-0(P,X)43-TC-95-M,,TTY	1.130E+07	2.210E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	6
A0009005	42-MO-0(D,X)43-TC-95-M,,TTY	8.100E+06	2.230E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	7
A0194109	42-MO-0(D,X)43-TC-95-M,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
B0109013	42-MO-0(D,X)43-TC-95-G,,TTY	1.170E+07	1.300E+07	J,JIN,38,2289,76	RANDA+	3CSRUJV	11
B0109013	42-MO-0(D,X)43-TC-95-M1,,TTY	1.170E+07	1.300E+07	J,JIN,38,2289,76	RANDA+	3CSRUJV	11
B0084007	42-MO-0(D,X)43-TC-95-M,,TTY	1.250E+07	1.250E+07	J,ARI,28,555,77	RANDA+	3CSRUJV	1
A0009010	41-NB-93(A,2N)43-TC-95-M,,TTY	1.760E+07	4.280E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	5
A0009008	42-MO-0(A,X)43-TC-95-M,,TTY	1.760E+07	4.200E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	5

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A0168097	42-MO-0(P,X)43-TC-96-G,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0009003	42-MO-0(P,X)43-TC-96,M+,TTY	1.130E+07	2.210E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	6
A0009006	42-MO-0(D,X)43-TC-96,M+,TTY	8.100E+06	2.230E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	7
A0194110	42-MO-0(D,X)43-TC-96,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
B0109013	42-MO-0(D,X)43-TC-96-G,,TTY	1.170E+07	1.300E+07	J,JIN,38,2289,76	RANDA+	3CSRUJV	11
B0084006	42-MO-0(D,X)43-TC-96,M+,TTY	1.250E+07	1.250E+07	J,ARI,28,555,77	RANDA+	3CSRUJV	1
A0009011	41-NB-93(A,N)43-TC-96,M+,TTY	1.200E+07	4.280E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	6
A0009009	42-MO-0(A,X)43-TC-96,M+,TTY	2.460E+07	4.200E+07	J,AE,40,66,7601	DMITRIEV+	4CCPFEI	4
A0168100	45-RH-103(P,3N)46-PD-101,IND,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0195033	47-AG-107(P,N)48-CD-107,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0194123	47-AG-107(D,2N)48-CD-107,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0168108	47-AG-0(P,X)48-CD-107,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0194124	47-AG-109(D,2N)48-CD-109,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0195036	48-CD-111(P,N)49-IN-111,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195077	48-CD-112(P,2N)49-IN-111,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195038	49-IN-113(P,N)50-SN-113,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195141	49-IN-115(P,3N)50-SN-113,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0194130	49-IN-113(D,2N)50-SN-113,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0195120	50-SN-118(P,N+P)50-SN-117-M,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0004004	49-IN-115(A,N+P)50-SN-117-M1,UND,TTY,,A	1.500E+07	4.320E+07	J,AE,39,135,75	DMITRIEV+	4CCPFEI	6
A0194131	50-SN-0(D,X)50-SN-117-M,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0004006	48-CD-0(A,X)50-SN-117-M1,,TTY	1.620E+07	4.200E+07	J,AE,39,135,75	DMITRIEV+	4CCPFEI	5
A0195079	52-TE-124(P,2N)53-I-123,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
B0169002	52-TE-124(P,2N)53-I-123,,TTY	1.200E+07	2.580E+07	J,ARI,28,765,77	KONDO+	1USABNL	2
A0234016	52-TE-122(D,N)53-I-123,IND,TTY	1.071E+07	3.301E+07	J,ARI,34,1425,83	ZAIDI+	2GERJUL	18
A0128002	52-TE-122(D,N)53-I-123,,TTY	4.000E+06	4.000E+06	J,RRL,47,(3),151,81	BEYER+	3DORROS	1

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B0169002	52-TE-124(P,N)53-I-124,,TTY	1.200E+07	2.580E+07	J,ARI,28,765,77	KONDO+	1USABNL	2
A0195080	52-TE-125(P,2N)53-I-124,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168124	52-TE-0(P,X)53-I-124,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0078002	52-TE-0(P,X)53-I-124,,TTY	9.800E+06	2.220E+07	J,AE,49,329,80	DMITRIEV+	4CCPFEI	6
A0194140	52-TE-0(D,X)53-I-124,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0078003	52-TE-0(D,X)53-I-124,,TTY	9.500E+06	2.210E+07	J,AE,49,329,80	DMITRIEV+	4CCPFEI	6
A0078005	51-SB-0(A,X)53-I-124,,TTY	1.650E+07	4.390E+07	J,AE,49,329,80	DMITRIEV+	4CCPFEI	6
A0078004	52-TE-0(A,X)53-I-124,,TTY	1.920E+07	4.340E+07	J,AE,49,329,80	DMITRIEV+	4CCPFEI	6
A0195047	53-I-127(P,N)54-XE-127,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168129	53-I-127(P,N)54-XE-127-G,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV	4CCPFEI	1
A0194145	53-I-127(D,2N)54-XE-127,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	1
A0044001	53-I-127(A,4N)55-CS-127,IND,TTY	3.880E+07	4.360E+07	J,AE,44,524,78	DMITRIEV+	4CCPFEI	4
A0044002	53-I-127(A,2N)55-CS-129,IND,TTY	2.040E+07	4.360E+07	J,AE,44,524,78	DMITRIEV+	4CCPFEI	9
A0094004	67-HO-165(A,2N)69-TM-167,,TTY	1.700E+07	4.340E+07	J,AE,48,402,80	DMITRIEV+	4CCPFEI	12
A0070002	74-W-0(P,X)75-RE-186,,TTY,,,CALC	1.030E+07	2.230E+07	J,AE,48,122,80	DMITRIEV+	4CCPFEI	7
A0070003	74-W-0(D,X)75-RE-186,,TTY,,,CALC	8.700E+06	2.220E+07	J,AE,48,122,80	DMITRIEV+	4CCPFEI	8
A0195101	80-HG-202(P,2N)81-TL-201,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195152	81-TL-203(P,3N)82-PB-201,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168183	81-TL-203(P,3N)82-PB-201-G,,TTY,,A	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1
A0195060	81-TL-203(P,N)82-PB-203,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0195151	81-TL-205(P,3N)82-PB-203,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	1
A0168185	81-TL-0(P,X)82-PB-203-G,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	1

ACCESSION NUMBER	REACTION	ENERGY(EV) MIN	ENERGY(EV) MAX	REFERENCE	AUTHOR	INSTITUTE	DATA LINES
A01951103	82-PB-206(P,2N)83-BI-205,,TTY	2.200E+07	2.200E+07	J,YK,,(2),57,83	DMITRIEV	4CCPFEI	
A01681186	82-PB-0(P,X)83-BI-205,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	
A01194207	82-PB-0(D,X)83-BI-205,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	
A02870I9	82-PB-206(P,N)83-BI-206,,TTY	1.040E+07	1.040E+07	J,JRN,82,135,84	ISSHIKI+	2JPNIOH	
A01681187	82-PB-0(P,X)83-BI-206,,TTY	2.200E+07	2.200E+07	J,YK,44,(5),43,81	DMITRIEV+	4CCPFEI	
A01194208	82-PB-0(D,X)83-BI-206,,TTY	2.200E+07	2.200E+07	J,YK,,(4),38,82	DMITRIEV+	4CCPFEI	

ANALYSIS OF THE CROSS SECTION DATA FOR THE PRODUCTION OF SHORT-LIVED LIGHT POSITRON EMITTER ISOTOPES WITH THE DEBRECEN CYCLOTRON

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Published production cross section data were analysed for ^{11}C (20.4 min), ^{13}N (10.0 min), ^{15}O (122.2 s) and ^{18}F (109.8 min) from the point of view of our cyclotron having beams of H^+ (up to 18 MeV), D^+ (up to 10 MeV), $^3He^{++}$ (up to 24 MeV) and $^4He^{++}$ (up to 20 MeV).

1. Introduction

An MGC-type cyclotron, made by the Jefremov Institute for Electro-Physical Equipment, Leningrad, USSR, was put into operation at the end of the year 1985. The machine accelerates protons (from 5 to 18 MeV^o), deuterons (from 3 to 10 MeV^o), ^3He (from 8 to 24 MeV^o), alpha particles (from 6 to 20 MeV^o).

As the first and only cyclotron in Hungary, its beam-time is shared among the fields of basic nuclear and atomic physics, interdisciplinary research and practical applications, namely micro-constituents' analysis and wear measurements for the industry, agricultural and medical irradiations and isotope production.

By using the beam of this cyclotron the isotope production of ^{67}Ga (78 h) has been tried already by the National Pharmaceutical Institute, Budapest, and it shall be used in some Hungarian hospitals in course of this year. The production of some other isotopes for medical application,

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o The values relate to external beam.

namely ^{123}I (13 h), ^{201}Tl (73.5 h), ^{111}In (2.8 d) is also in preparation.

The next step in the isotope production, however, will be the manufacture of ultra short-lived isotopes, namely $^{11}_{6}C$ (20.39 min), $^{13}_{7}N$ (9.96 min), $^{15}_{8}O$ (122.24 s) and $^{18}_{9}F$ (109.77 min) for medical purposes during the next years. It is partly because of the medical significance of these isotopes, partly because this cyclotron is especially suitable for the production of these isotopes (see e.g. ref. 1-4).

In preparation for the above task, the first step is to survey the literature searching for production cross section data to find the most suitable reactions for the ultra short-lived isotopes concerned under our actual conditions. In the present paper a report is given on the results of this activity with a special emphasis on the data uncertainties and gaps found.

2. Procedure and experiences on search for data in the literature

To look for the pertaining papers first of all the INIS System of IAEA, Vienna was used in an on-line operation from the National Technological Information Center and Library, Budapest. On the basis of the on-line information the abstracts of 194 papers were asked for and received from Vienna by mail. By using the abstracts it was possible to decide which papers are interesting in fact from our point of view and then the full texts of these papers were acquired. All important papers were found in our library or in Debrecen.

The INIS system, however, contains the literature only from the year 1975 and that is why we should use also the information from EXFOR (5) At the same time we have used some publications which were not included in either system.

3. Data for the production cross sections

In the course of the analysis at each short-lived isotope, first all reactions were looked over by which the radioisotope concerned can be produced. Only those reactions were studied further in detail in the case of which no enriched target was needed, because the energy range of the projectiles at our cyclotron does not necessitate the use of enriched targets. Of these cases those reactions were selected where the target was of gas phase because it is a great advantage in the production of ultra short-lived isotopes. If more than one reaction satisfying the above criteria were found, all of these reactions were considered only if there was less than a magnitude of order difference among the overall values for the production cross section.

3.1. ^{11}C. In this case 13 reactions were found in the literature with ^{11}C as an end-product. On the basis of the above three criteria only the reaction $^{14}N(p,\alpha)^{11}C$ should be investigated in detail. Fig. 1 shows the published production cross section data in the bombarding energy range of interest.

As it can be seen, practically all the measurements except those from ref. 7 give approximately the same results as regards the production cross section of ^{11}C at our cyclotron.

3.2. ^{13}N. For the end product ^{13}N, 8 reactions were found altogether. Our criteria allow only one reaction, namely $^{16}O(p,\alpha)^{13}N$ to use. It should be mentioned, however, that the maximum value for the production cross section in the case of another reaction, $^{14}N(p,pn)^{13}N$ is not an order of magnitude less than that for $^{16}O(p,\alpha)^{13}N$ but the 32 mb maximum value for ^{13}N was found at 20 MeV (18), and we did not succeed in finding any more details on this reaction in the literature.

In Fig. 2 it can be seen that there is a substantial disagreement with the other data from the point of view of ^{13}N production in case of ref 13 practically in the whole energy range concerned (9.6 - 15.0 MeV) and in case of ref. 16 and 17 at about 8 MeV bombarding energy

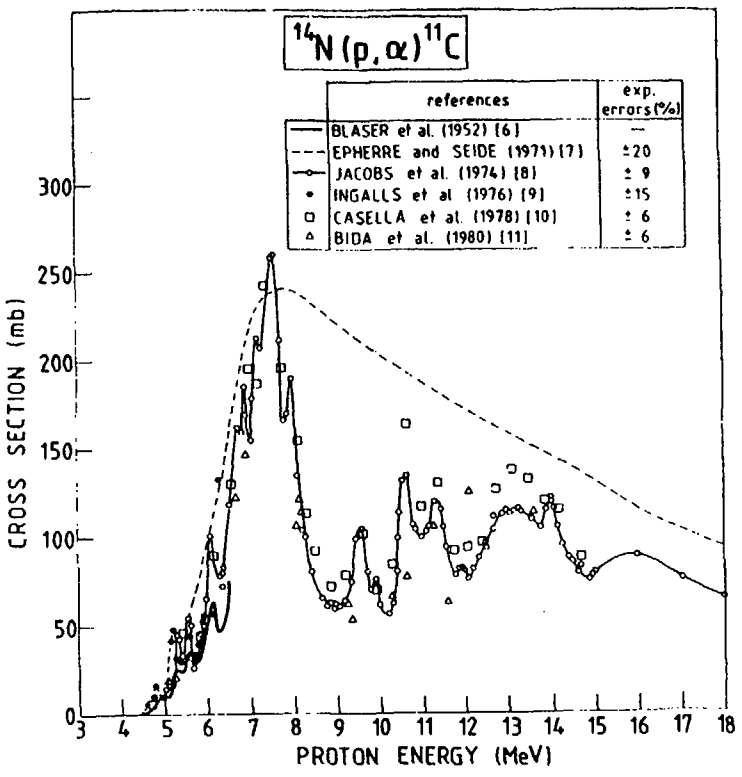

Fig. 1 Comparison of experimental cross section data for $^{14}N(p,\alpha)^{11}C$ reaction

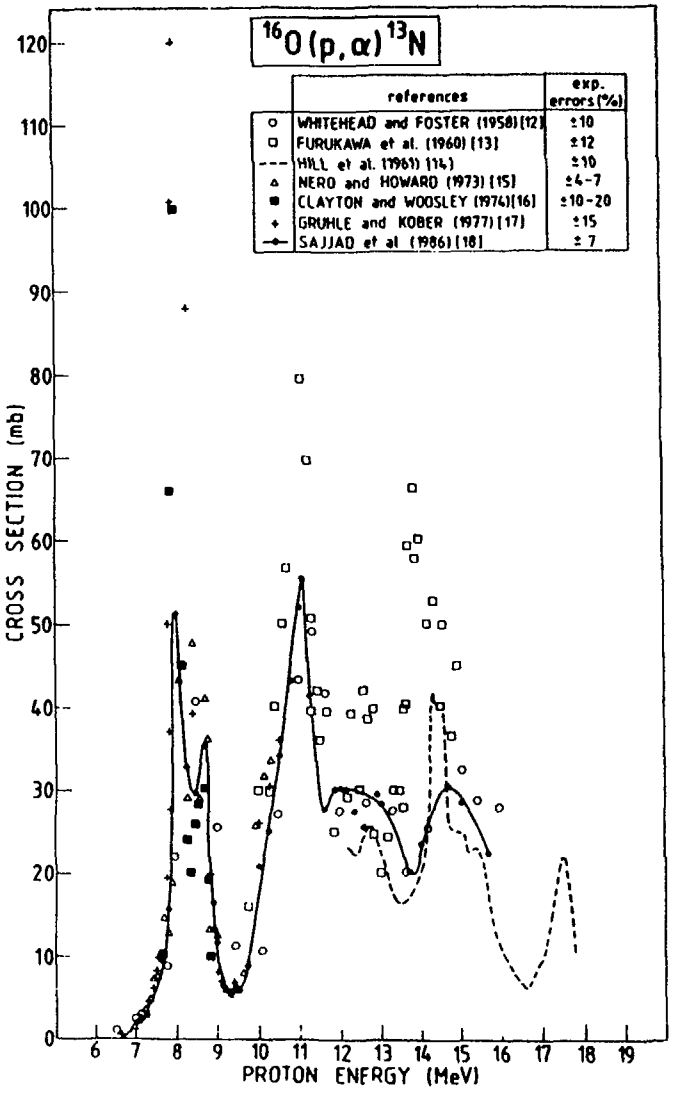

Fig. 2 Comparison of experimental cross section data for $^{16}O(p,\alpha)^{13}N$ reaction

3.3. ^{15}O. Altogether 5 reactions were found with ^{15}O end-product in the literature. After using our criteria only the reaction $^{14}N(d,n)^{15}O$ was considered in details.

Fig. 3 shows the cross section data found for this case. Two measurements are in a rather good agreement, while a relative old data series (19) strongly disagrees and a somewhat newer one (20) disagrees because of the supposedly erroneus calibration of the detector NaI(Tl) (cf. ref. 21.).

3.4. ^{18}F. Out of the observed 10 reactions concerned, two are considered here in details, namely $^{16}O(^{3}He,p)^{18}F$ and $^{20}Ne(d,\alpha)^{18}F$. In the former case, however, the reaction $^{16}O(^{3}He,n)^{18}Ne$ is also included because the ^{18}Ne decays by positive beta decay into ^{18}F with a half-life of 1.5 s.

As it is shown in the Fig. 4 the cross section for $^{16}O(^{3}He,p)^{18}F$ data in our range of interest agrees rather well from our point of view. It should be mentioned, however, that there is only one series of measurements below 10 MeV of bombarding energy.

As regards the $^{20}Ne(d,\alpha)^{18}F$ (Fig.5) the two published series of values (25,27) for the cross section are in a rather definite disagreement in the whole bombarding energy range of interest.

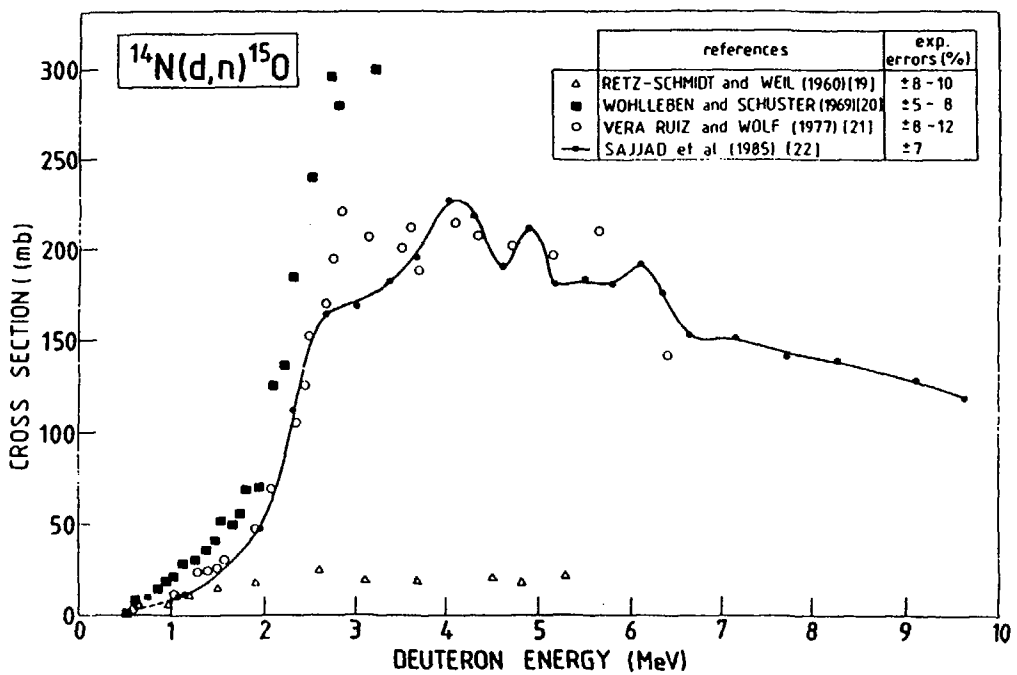

Fig. 3 Comparison of experimental cross section data for $^{14}N(d,n)^{15}O$ reaction

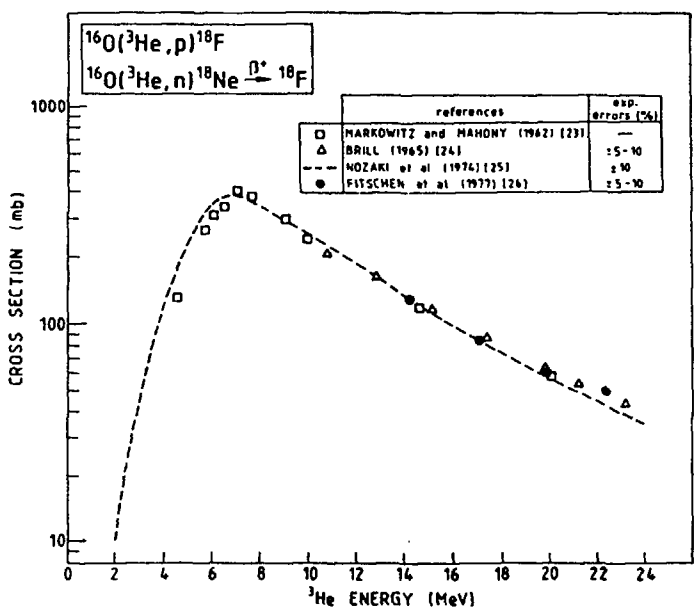

Fig. 4 Comparison of experimental cross section data for $^{16}O(^{3}He,p)^{18}F$ and $^{16}O(^{3}He,n)^{18}Ne \xrightarrow{\beta^+} {}^{18}F$ reactions

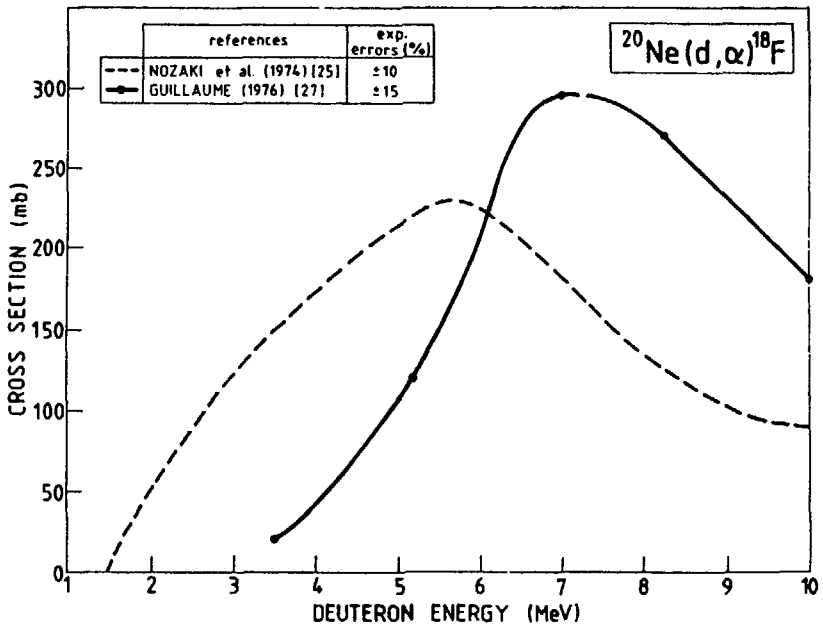

Fig. 5 Comparison of experimental cross section data for $^{20}Ne(d,\alpha)^{18}F$ reaction

4. Final remarks

The literature for the production cross sections for four ultra short-lived isotopes ^{11}C, ^{13}N, ^{15}O and ^{18}F was analysed on the basis of some specified criteria. One or other of these criteria of course, can be questioned in one or other actual case.

Furthermore, if one would like to produce two or more ultra short-lived isotopes simultaneously, other target materials and reactions for producing ^{11}C, ^{13}N, ^{15}O or ^{18}F should be taken into account. E.g. melted B_2O_3 target can be used for the simultaneous production of ^{11}C via $^{11}B(p,n)^{11}C$ reaction and for ^{13}N via $^{16}O(p,\alpha)^{13}N$ reaction (28) For the use of melted target, however, the most proper arrangement is a vertical beam line, which we have at our cyclotron facilities (29).

The authors special thanks are due to Dr. P. Roboz (OMIKK, Budapest) for the help to acquire the information from INIS (IAEA, Vienna) by an on-line connection.

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On the Cross Sections for ^{52}Fe Production Reactions

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ABSTRACT

The reaction cross-section data such as ^{58}Ni(p,p2n)^{52}Fe etc. were surveyed and compiled. The production yields of ^{52}Fe were also examined. The present status of cross section is discussed.

As a part of the compilation of nuclear reaction data concerning radioisotope production for medical applications, the excitation functions and production yields for ^{52}Fe so far appeared in publications were reviewed.

The positron-emitting ^{52}Fe ($T_{1/2}$ 8.3hr) has been recognized as a useful agent for bone marrow imaging in studying the erythropoietic tissue or other metabolic processes. Other iron isotopes such as ^{55}Fe and ^{59}Fe are not suitable for this purpose because of that their half-lives are too long and the energies of accompanying γ-rays too high or low. They act as harmful or interfering impurities for patients as well as for measurements. It is therefore requested to establish a ^{52}Fe production method which is free of other iron impurities as much as possible.

^{52}Fe is also used as the parent nuclide for the ^{52}Fe-^{52m}Mn generator system which separates ^{52m}Mn ($T_{1/2}$ 21.1m). Figure 1 shows the simplified decay schemes of relevant iron isotopes. Radiomanganese has shown its usefulness as an imaging agent in myocardial diagnosis. ^{52}Fe

containing other radioiron impurities can be used for the generator system because the iron impurities result in no interfering manganese daughters. In this case, ^{52}Fe producing reactions which would be accompanied with significant production of other radioiron become usable.

Experimental excitation functions for the ^{52}Fe producing reactions, fundamental data to evaluate production yields, have not sufficiently been accumulated to make evaluation for a recommended curve. Table 1 shows the experimental excitation functions, and Table 2 the production yields measured both appeared in publications to date.

Although there are a variety of production methods available, a rather limited number of schemes have been conveniently utilized in practices for nuclear medical applications so far. In practical point of view, noticeable reactions are (^{3}He,3n), (α,2n), (p,4n) and (p,spallation).

The $^{nat}Cr(^{3}He,3n)^{52}Fe$ reaction seems the most suitable to produce the ^{52}Fe almost free of iron impurities. Greene et al. measured the excitation function in the energy range of 23 - 44 MeV.(7) Figure 2 shows their results. The reaction is feasible with a relatively low energy cyclotron.

The ^{nat}Cr (α,2n)^{52}Fe reaction also produces a considerable amount of ^{55}Fe impurities, nevertheless the product is adequately utilizable for a generator system.

The ^{nat}Mn (p,4n)^{52}Fe reaction provides ^{52}Fe in relatively high yields with low iron impurities. Suzuki measured the excitation function and calculated the production yields recently.(1) The results are shoen in Figure 3. He reported that the actual yields were 85 - 93 % of calculated values. The manganese target used brought about no serious problem in separating carrier free ^{52m}Mn from the generator system. This reaction seems very suitable for the production of ^{52}Fe for the generator system when proton beams of around 60 MeV are available.

The (p,spallation) reaction which requires a high energy facility of larger scale has been reported to give the highest yields for ^{52}Fe.

Generally speaking, the cross section data for ^{52}Fe production reactions are still insufficient and further precise experiments are requested.

Table 1 Excitation Functions for ^{52}Fe

Particle	Reaction	Energy(peak) (MeV)	σ_{max} (mb)	Ref.
p	^{55}Mn(p,4n)	40 - 73(54)	1.4	1) K.Suzuki
	^{54}Fe(p,p2n)	33 - 44(45)	1.4	2) R.Michel
	^{54}Fe(p,t)	18 - 23	0.3	3) B.L.Cohen
	^{54}Fe(p,dn)	33 - 60(45)	4	4) I.R.Williams
	^{59}Co(p,spall)	59 - 98(77)	0.44	5) R.A.Sharp
	^{58}Ni(p,αp2n)	42 - 56	1.8	6) S.Tanaka
^{3}He	$^{52}Cr(^{3}He,3n)$	23 - 44(35)	5	7) M.W.Greene
α	^{59}Co(α,3p8n)	113 - 170	0.26	8) R.Michel
	^{54}Fe(α,α2n)	38 - 40	0.34	9) S.Tanaka
^{6}Li	$^{54}Fe(^{6}Li,X)$	55 - 94	4.8	10) J.Jastrzebski

Table 2 Production Yields for ^{52}Fe

Particle	Reaction	Energy (MeV)	Production Yield (μCi/μAh)	$^{55}Fe/^{52}Fe$ (percent)	Ref.
p	$^{55}Mn(p,4n)$	65	160	< 3	11
	$^{55}Mn(p,4n)$	70 - 50	200	0.7	12
	$^{55}Mn(p,4n)$	70	98	0.7	13
	$^{55}Mn(p,4n)$	73 - 39 60 - 39	670 380	0.44 0.50	1
	$^{55}Mn(p,4n)$	70	110		14
	$^{58}Ni(p,spall)$	193.0	50	0.8	13
	Cu(p,spall) Fe(p,spall)	590 590	0.25 mb 0.80 mb		15
	Cu(p,spall) Fe(p,spall)	590 590	0.27 mb 0.675 mb		16
	Ni(p,spall)	588	700	3.3	17
	Ni(p,spall)	200	67		14
	Ni(p,spall)	800	3300		14
	Ni(p,spall)	800	138		18
^{3}He	$^{52}Cr(^{3}He,3n)$	45.5	50	< 0.001	7
	$^{52}Cr(^{3}He,3n)$	23	0.7	0.3	19
	$^{52}Cr(^{3}He,3n)$	40	50		20
	$^{52}Cr(^{3}He,3n)$	33	20	< 0.07	21
	$^{52}Cr(^{3}He,3n)$	45 - 30	22.5		22
α	$^{50}Cr(\alpha,2n)$	65	8/gm	5 - 6	23
	$^{50}Cr(\alpha,2n)$	30	3.3	14	24
	$^{50}Cr(\alpha,2n)$	30	0.5		25
^{12}C	$Cu(^{12}C,spall)$	1032	0.35 mb		26

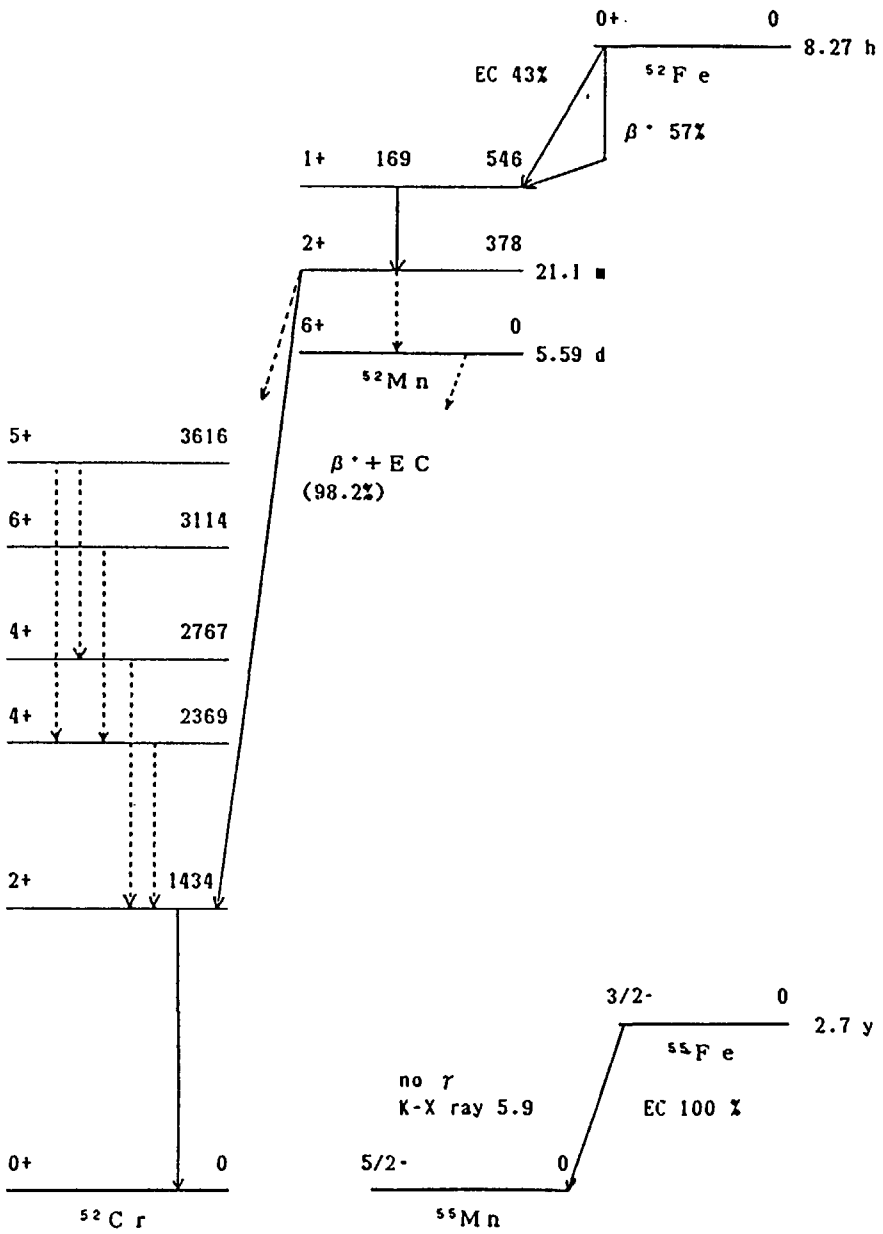

Fig 1

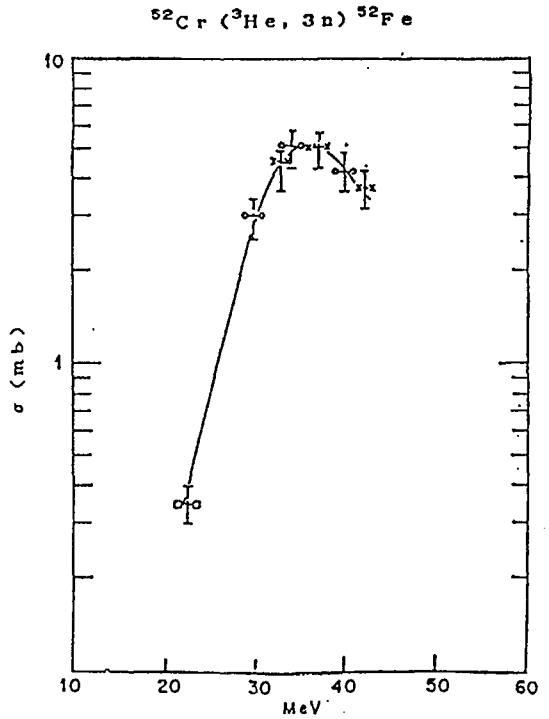

Fig 2

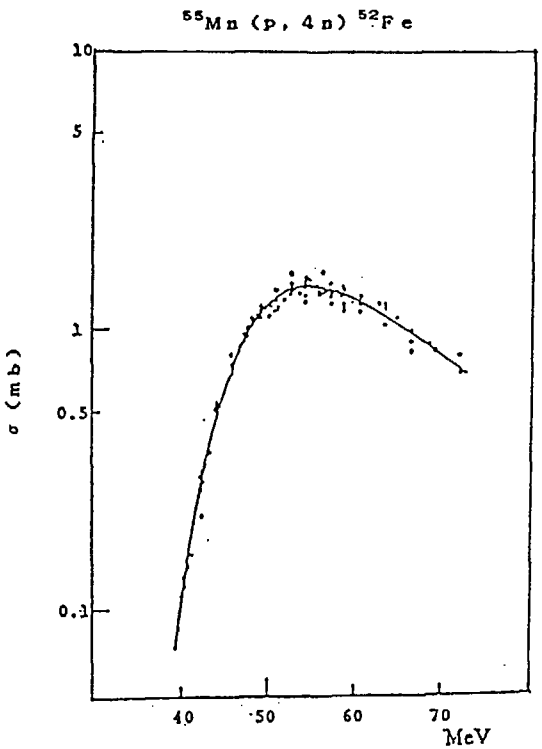

Fig 3

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On the Cross Sections for ^{77}Br Production Reactions

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Abstract

Excitation functions for ^{77}Br and ^{77}Kr production reactions, such as $^{75}As(\alpha,2n)$, $^{79}Br(p,3n)^{77}Kr$ etc., are reviewed at a standpoint of the data evaluation. Some comparison between measured and calculated cross sections by the computer code ALICE are shown. And, a brief review on the use of decay data in the measurements of these reaction cross sections is also given.

One of roles of the evaluation of nuclear reaction data is to provide the best reference for the bench mark test of computer codes on the calculation of excitation functions and to provide the basic data for estimating the optimum irradiation conditions for the cyclotron production of radionuclides. From this point of view, the status of the experimental excitation functions for the production reactions of ^{77}Br ($T_{1/2}$ = 56.07 hr) were discussed.

Radioactive isotopes of bromine have been considered to be suitable agents to prepare labelled radiopharmaceuticals. At present some comprehensive reviews exist on productions and applications of the isotopes. These are:

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However, radiobromine compounds have been rarely used in hospitals and clinics in Japan. (see Appendix)

Bromine-77 can be produced directly by charged-particle reactions on arsenic, selenium or bromine and also be obtained indirectly as the decay product of ^{77}Kr ($T_{1/2}$ = 77.4 min) or the decay chain of ^{77}Rb ($T_{1/2}$ = 3.7 min)-^{77}Kr. And the spallation reactions with high-energy protons on molybdenum are also used to produce bromine-77. Since a method of production of carrier-free ^{77}Br by bombarding alpha particles on arsenic was developed for medical use by Helus [1] , various types of reactions and target assemblies have been proposed to produce ^{77}Br or ^{77}Kr. Thick target yields and cross sections for the production of these nuclides were measured for various bombarding conditions and target systems [2] - [23] . See Table 1a and 1b.

Excitation functions

The $^{75}As(\alpha,2n)^{77}Br$ (^{75}As has 100% natural abundance) is the most widely used reaction for the production of ^{77}Br with bombarding energies of 28-30 MeV. The excitation functions were given by Waters and Stöcklin [3] , Nozaki et al. [13] , Alfassi et al. [17] and Qaim et al. [23] . Waters and Stöcklin [3] reported cross sections of this reaction for alpha energies of 13.8 to 28.1 MeV, Alfassi et al. [17] for energies of 25 to 140 MeV, and Qaim et al. for energies of 15 to 28 MeV [23] . Figure 1 shows these data to be in good agreement in the energy range of 25 to 28 MeV, except for those of Nozaki et al. [13] . But these data would become more reliable if Alfassi had measured cross sections in the energy of 20 MeV, or if Waters or Qaim had measured in the energies higher than 30 MeV. Qaim et al. [23] pointed out the discrepancy to attribute partially to the use of different target materials. In Fig. 1, theoretical cross section calculated using the code ALICE/Livermore/82 are also included. Qaim et al. [23]

have alsó measured cross sections of the reaction $^{75}As(\alpha,2n)^{77m}Br$ and cross section ratios for the isomeric pair.

Measurements of the excitation function for the reaction $^{79}Br(p,p2n)^{77}Br$ are difficult. Because, as shown in Fig. 2, the ^{77}Br nuclideO is also produced from the decay of ^{77}Kr by the reaction $^{79}Br(p,3n)$ occurring simultaneously in the bombarding process. Moreover, in proton energies higher than the threshold of $^{81}Br(p,p4n)$ reaction, when natural bromine is used as target materials, The ^{77}Br nuclide is also produced from this reaction. For the reaction $^{81}Br(p,p4n)^{77}Br$, there is a similar situation. These data were measured by Dikšić et al. [11] using the targets of 95.06% enrichment for ^{79}Br and of 97.81% for ^{81}Br. Dikšić et al. [11] also compared cross sections for the (p,*xn*) and (p,p*xn*) reactions on ^{79}Br and ^{81}Br with some theoretical predictions by intranuclear cascade and two pre-equilibrium models followed by equilibrium evaporation. But he concluded that none of the three computer codes was able to reproduced all excitation functions satisfactorily.

Excitation function for the $^{79}Br(p,3n)^{77}Kr$ reaction on the ^{79}Br enriched was obtained by Dikšić et al. [11] only. But. if bombarding energies are below the threshold of the $^{81}Br(p,5n)^{77}Br$ reaction, excitation function on natural bromine can be used for the evaluation. Some comparisons of experimental excitation functions of this reaction are shown in Fig. 2 and 3, and there are considerable disagreements between those measurement data. In all these experiments, sodium bromide (NaBr) was used as target materials.

$^{77}Se(p,n)^{77}Br$ and $^{78}Se(p,2n)^{77}Br$ reactions are also used practically. Selenium consists of many isotopes. The enriched target used prevents cross contamination with other isotopes. Only one data has been reported by Janssen et al. [15] .

In the Se + ^{3}He reactions enriched targets should be used.too. Excitation functions for these reactions were given by He Youfeng et al. [20] on enriched targets. Although the values of cross sections for $Se(^{3}He,xn)^{77}Kr$ reactions are comparable to those of other ^{77}Kr production reactions, De Jong et al. [10] reported that thick target yields were lower than other reactions as figures of one to two order.

This may be due to kind of the target materials. And this suggests that the kind of target materials and bombarding conditions affect to measurements of the cross section strongly.

The production of ^{77}Br by the spallation process allows the preparation of a batch with larger activities. The cross sections for the spallation of molybdenum with 800-MeV proton were measured [16] .

Monitor reactions

Above-mentioned measurements of excitation functions were carried out by using stacked foil techniques. The materials for degradation of bombarding particles or for separation of each foils provide monitor reactions. Following reactions were used as monitor:

$^{12C}(p,pn)^{11}C$,
$^{27}Al(p,3pn)^{24}Na$,
$^{63}Cu(p,p2n)^{61}Cu$,
$^{63}Cu(p,2n)^{62}Zn$,
$^{63}Cu(p,n)^{63}Zn$,
$^{63}Cu(p,x)^{61}Cu$,
$^{27}Al(d,3p2n)^{24}Na$,
$^{63}Cu(^{3}He,p2n)^{62}Zn$,
$^{65}Cu(^{3}He.2n)^{66}Ga$.
$^{65}Cu(p,n)^{65}Zn$.
$Ti(^{3}He,x)^{48}Ti$, and
$^{63}Cu(\alpha,n)^{66}Ga$.

For the cross sections of $^{27}Al(p,3pn)^{24}Na$ reaction. the value of 6-8% were cited as errors. De Jong et al. [10] reported that the beam current monitoring with 65Zn and ^{66}Ga activites from $^{65}Cu(^{3}He.p3n)^{62}Zn$ and $^{65}Cu(^{3}He,2n)^{66}Ga$ reactions agreed within 10%. The errors in the cross sections of $^{63}Cu(p,n)^{63}Zn$ and $^{63}Cu(p,2n)^{62}Zn$ reactions for protons of energies higer than 30 MeV and the 40 MeV were estimated to be 15% for natural copper target owing to the contributions from $^{65}Cu(p,3n)^{63}Zn$ and $^{65}Cu(p,4n)^{62}Zn$ reactions. respectively [11] .

Decay data

There were confusing differences among decay data used in activity measurements. The half-life of 56 hr for the nuclide ^{77}Br has been widely used, while Blue and Benjamin [2] used 59 hr and Blessing et al. [17] used 57 hr. As for the gamma-rays abundance of ^{77}Br, Dikšić et al. [11] used 26.0% for the 239-keV γ-rays, but other authors used 22.8 or 23.1 or 23.8%. Weinreich and Knieper [21] used 82.2% for the 130-keV γ-rays and 39.3% for 147-keV γ-rays of the nuclide ^{77}Kr, but all other authors used values of 87.3% and 40.9%, respectively.

Conclusions

At present, the evaluation of excitation functions for the production of ^{77}Br or ^{77}Kr are difficult, because excitation functions publised depend upon conditions of experiments. Moreover, unexplainable discrepancies still exist among those values in some type reactions. As for the decay parameters of the nuclides ^{77}Br or ^{77}Kr and those of monitor reaction products, different values are used in activity measurements in some case. And old and unevaluated decay data used. Of course, some decay data are not sufficiently reliable, and evaluation works to these data are slowly progressing.

Then, we hope that IAEA takes actions

- to establish the standard procedure, including monitor reactions and calibration of beam energies, and to select suitable target materials for measurements of "good" excitation functions, and
- to promote establishing the precise decay parameters , such as the as the half-life and the intensities of prominent gamma-rays of related radioactive nuclides.

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Appendix

In Japan, the statistical data for the annual use of radionuclides can get from a governmental agency. Among unsealded radioradionuclides used as in vivo diagnostic pharmaceuticals, the ^{99m}Tc nuclide accounts for an overwhelming majority. While the nuclides ^{77}Br or ^{77}Kr have been not rarely used. Fig. 5 shows annual amounts of unsealded radioactive nuclides used as in vivo diagnostic agents for hospitals and clinics in fiscal years of 1976-1985 in Japan.

Table 1a. Production reactions and measured quantities

Reaction	Measured quantities	
	Thick target yield	Excitation function
$^{75}As(\alpha,2n)^{77}Br$	Helus [1] Nunn et al. [5] Nozaki et al. [13] Alfassi et al. [17] Blessiing et al. [18] Dmitriev et al. [19] Qaim et al. [23]	Water et al. [3] Nozaki et al. [13] Qaim et al. [23]
$^{75}As(\alpha,2n)^{77m}Br$	Qaim et al. [23]	Qaim et al. [23]
$^{77}Se(p,n)^{77}Br$	Norton et al. [8] ‡ Janssen et al. [15] ‡	Janssen et al. [15] ‡
$^{78}Se(p,2n)^{77}Br$	Madhusudhan et al. [14] ‡ Janssen et al. [15] ‡	Janssen et al. [15] ‡
$^{79}Br(p,p2n)^{77}Br$	Dikšić et al. [6] ‡	Dikšić et al. [6] ‡
$^{81}Br(p,p4n)^{77}Br$	Dikšić et al. [6] ‡	Dikšić et al. [6] ‡
$Br(d,pxn)^{77}Br$	Qaim et al. [7]	Qaim et al. [7]
$^{76}Se(^{3}He,pn)^{77}Br$	He Youfeng et al. [20] ‡	He Youfeng et al. [20] ‡
$^{77}Se(^{3}He,p2n)^{77}Br$	He Youfeng et al. [20] ‡	He Youfeng et al. [20] ‡
$Se(p,xn)^{77}Br$	Dmitriev et al. [19] Nozaki et al. [13]	Nozaki et al. [13]
$Se(d,xn)^{77}Br$	Dmitriev et al. [19]	
$Se(\alpha,xn)^{77}Br$	Dmitriev et al. [19]	
$Mo(p,spallation)^{77}Br$	Grant et al. [16]	

‡ enriched targets were used.
§ no data given by authors.

Table 1b. Production reactions and measured quantities

$^{79}Br(p,3n)^{77}Kr$	Dikšić et al. [6] ‡	Lundqvist et al. [12]
	Nozaki et al. [13]	Nozaki et al. [13]
	De Jong et al. [9]	De Jong et al. [9]
	De Jong et al. [10]	Diksic et al. [11] ‡
	Weinreich et al. [21]	Weinreich et al. [21]
$^{81}Br(p,5n)^{77}Kr$	Lundqvist et al. [12]	Lundqvist et al. [12]
	Nozaki et al. [13]	Nozaki ei al. [13]
	De Jong et al. [9]	De Jong et al. [9]
		Dikšić et al. [6] ‡
$Br(d,xn)^{77}Kr$	Qaim et al. [7]	Qaim et al. [7]
$^{76}Se(^{3}He,2n)^{77}Kr$	De Jong et al. [10]	He Youfeng et al. [20] ‡
	He Youfeng et al. [20] ‡	
$^{77}Se(^{3}He,3n)^{77}Kr$	De Jong et al. [10]	He Youfeng et al. [20] ‡
	He Youfeng et al. [20] ‡	
$^{71}Se(^{3}He,4n)^{77}Kr$	De Jong et al. [10]	
$Se(^{3}He,xn)^{77}Kr$	He Youfeng et al. [20]	
$^{76}Se(\alpha,3n)^{77}Kr$	Blue et al. [2] ‡§	
$Br(\alpha,xn)^{77}Rb$	Helus et al. [4] §	

‡ enriched targets were used.
§ no data given by authors.

Table 2. Target materials used in some references

Authors	Materials
Water et al.[3]	As deposited by electic discharge on Al foil in arsenie gas.
Nozaki et al.[13]	Stacked $Mg_2As_2O_7$ foils.
Alfassi et al.[17]	Metallic As suspended in a self-suporting polystyrene film.
Qaim et al.[23]	Electrolytic deposition of arsenic on Cu-baking.

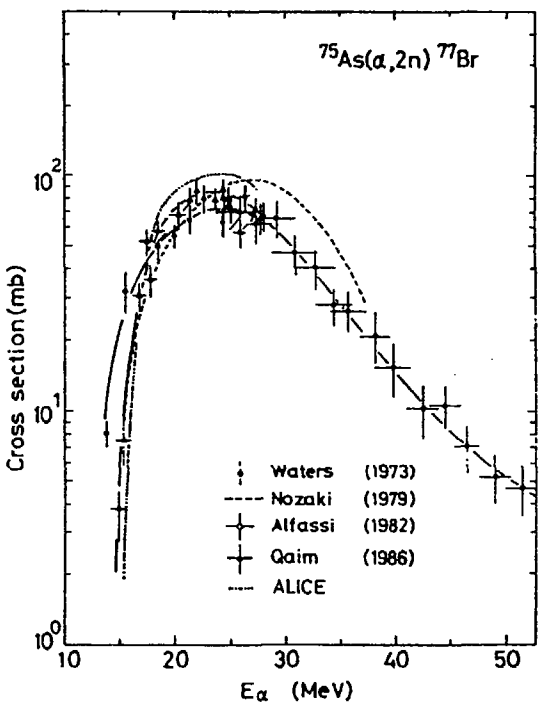

Figure 1. A comparison of excitation functions for the reaction $^{75}As(\alpha,2n)^{77}Br$. Included is that calculated by code ALICE/Livermore/82.

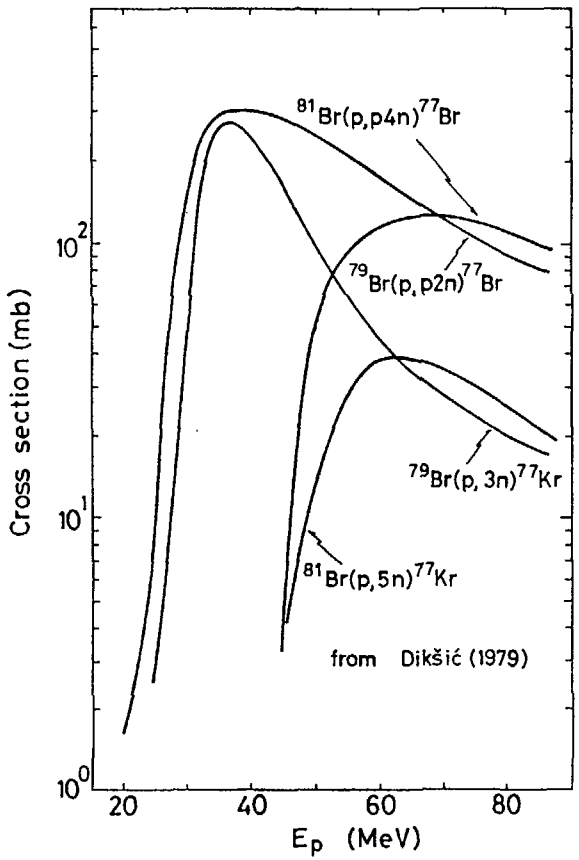

Figure 2.

Excitation functions for $^{79,81}Br$ + proton reaction.

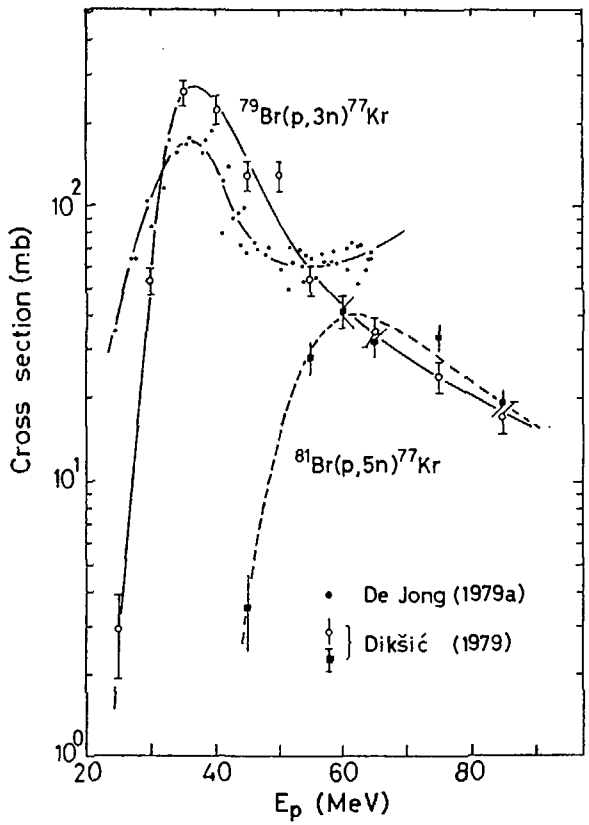

Figure 3.

A comparison of of excitation functions for the $^{79}Br(p,3n)\ ^{77}Kr$ and the $^{81}Br(p,5n)^{77}Kr$ reactions.

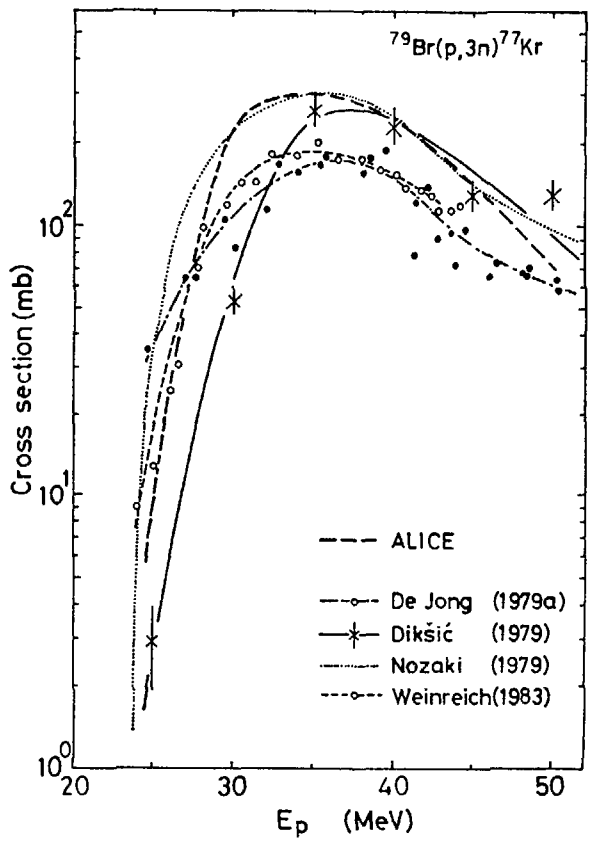

Figure 4.

A comparison of excitation functions for the reaction $^{79}Br(p,3n)^{77}Kr$. Including is that calculated by code ALICE/Livermore/82.

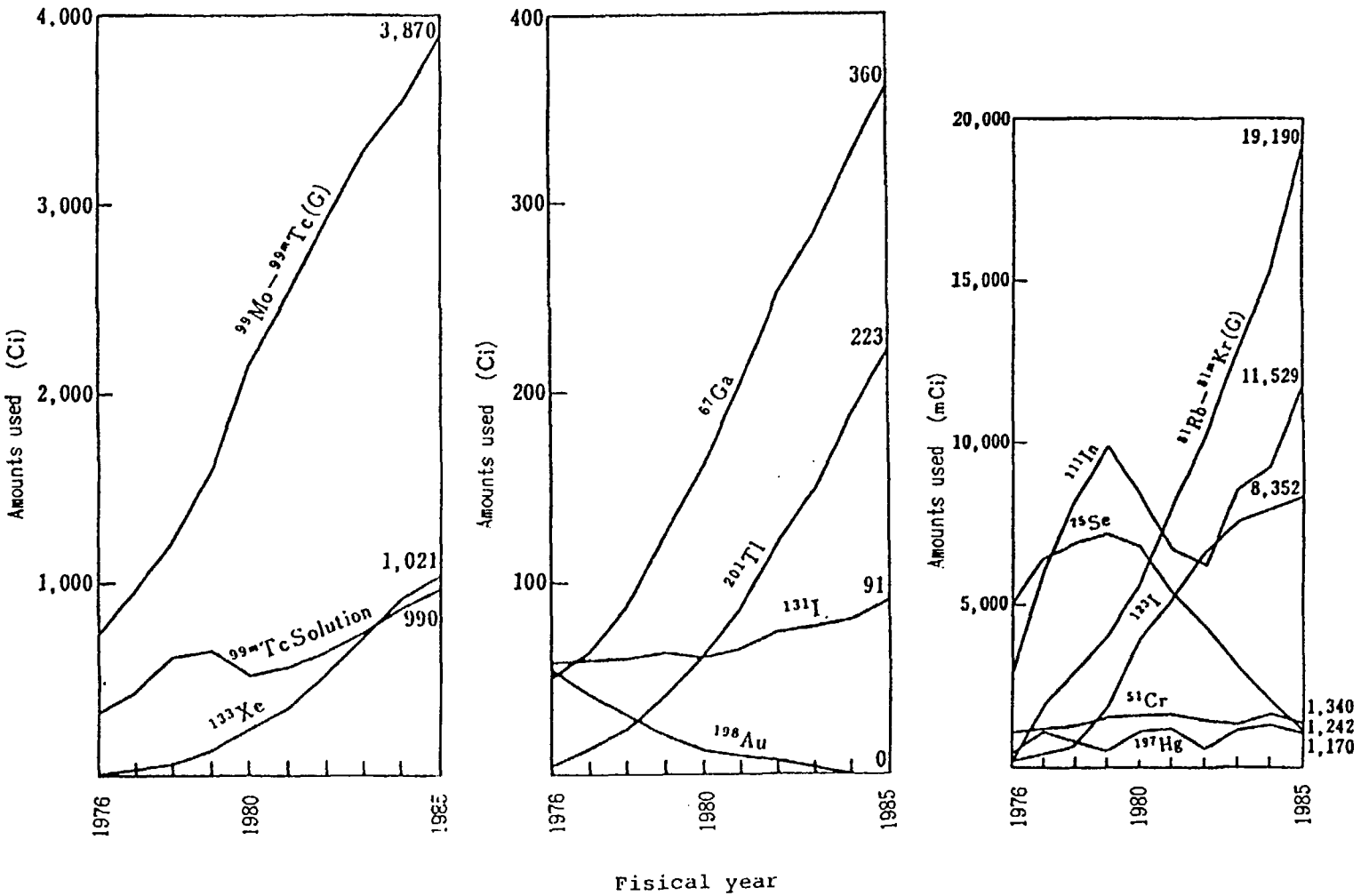

Figure 5. Annual amounts of radionuclides used for in vivo medical diagnostics in hospitals and clinics in Japan at period of 1976-1985 fiscal year.

On the Cross Sections for ^{123}I Production Reactions

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Abstract

The cross-section data of the nuclear reactions such as $^{124}Te(p,2n)^{123}I$, $^{127}I(p,5n)^{123}Xe$ and $^{122}Te(d,n)^{123}I$ were surveyed and compared with the results of calculations by computer codes. The present status of cross section data is discussed.

Due to the suitable nuclear decay properties, ^{123}I is considered to be one of the best radionuclides for in vivo diagnostic nuclear medical studies using single photon emission computed tomography. Though there were proposed over twenty kinds of reactions to produce ^{123}I, there are several points to select these reactions, that is, the price of enriched isotope for a target, ease of recovery and recovery percentage of the isotope after irradiation, beam requirements whether the kind of incident beam and its energy are easily available, production yield rate, chemical separation yield, and impurity of other radioactive iodine isotopes for the final product, etc.

$^{124}Te(p,2n)$ reaction: This reaction has been used most extensively in the routine production of ^{123}I. Its excitation function is shown in Fig. 1[1]. Using 99.87 % isotopically enriched isotope, each point is determined with uncertainties of between 4 % and 12 % except the lowest energy point. The cross section is also measured with 91.86 % enriched isotope as a target. As a whole, the cross sections were measured by precision of about 10 %, the production rates as a function of energy reported by a different author differ more than about a factor of two.

There are many reports concerning practical product yield of ^{123}I which were shown in Fig. 2. As shown in the figure, the reported product yields are scattered in wide range of the yield. A part of reasons could be attributted to the loss of ^{123}I during irradiation, if the precaution is not made, the product yields become a function of beam intensities due to loss of iodine during the irradiation.

$^{127}I(p,5n)^{123}Xe$ reaction: The excitation functions have been reported by four different authors[2-5]. The situation is shown in Fig. 3 in which the values reported by Syme et al. are most elaborated one showing various errors included in the measurement. Each author took the precaution for the loss of target or reaction products during irradiation. One of the reason of differences of these absolute cross sections may be attributed to the value of beam current integration. Paans and Wilkins have measured the beam current directly. Diksic and Syme used the monitor reaction such as $^{27}Al(p,3pn)^{24}Na$ and $^{12}C(p,pn)^{11}C$. It seems that the results of Diksic and Syme are comparatively good.

Deutron induced reactions: $^{122}Te(d,n)^{123}I$[6] and $^{127}I(d,6n)^{123}Xe$[7] reactions have been reported. Zaidi insisted that $^{122}Te(d,n)$ reaction can produce ^{123}I with better purity than

using the $^{124}Te(p,n)$ reaction. The cross sections are shown in Fig. 4. There is only one measurement concerning absolute value for this reaction.

Alpha induced reactions; The $^{121}Sb(\alpha,2n)^{123}I$[8], $^{123}Sb(\alpha,4n)^{123}I$ and also $^{122}Te(\alpha,3n)^{123}Xe$ reactions are the scope of interest. The cross sections $^{121}Sb(\alpha,2n)^{123}I$ have been measured from the interest to compair with theory. Absolute cross sections in the energy range from threshold to 27 MeV have been measured and compared with a statistical theory in which the competition of decay was taking into account. The cross sections were also measurmed with natural Antimony target (^{121}Sb is 57.3 % and ^{123}Sb is 42.7 %)[9]. These data are useful to produce ^{123}I.

The product yield rate of $^{123}Sb(\alpha,4n)^{123}Xe$ has been measured in the incident energy range of between 50 to 75 MeV.

The $^{122}Te(\alpha,3n)$ reaction is one of the method to produce ^{123}Xe with minimum impurity such as ^{124}I, ^{125}I etc, however its cross section is not found in our survey.

Other reactions; Among other reactions explained above, ^{3}He induced reactions with $^{122,123}Te$ as targets have high ^{123}Xe yield compared with alpha particle induced reactions. However there are no reports on the absolute cross sections. The cross sections have been measurmed with natural Antimony taget[9].

It is known that the spallation reaction induced by high energy protons have relatively high yield of ^{123}I[10]. The cumulative cross sections for ^{123}Xe decrease slowly with incident proton energy. Typical cumulative cross section values are 40 and 29 mb at 342 and 660 MeV respectively.

About impurity; The long lived ^{124}I(4.2 d), ^{125}I(60.2 d) etc. increase the absorbed dose of a patient when his thyroid is administrated by ^{123}I. In addition, the thomography is obscured by contamined gamma-rays. Because these reasons, the existence of impurity in ^{123}I is the most critical factor to determine the producing reaction. Using 96.2 % isotopically enriched ^{124}Te as a target with (p,2n) reaction, the impurity of ^{124}I and ^{125}I in ^{123}I were 0.05 % and 0.5 % respectively. This value is comparable for the $^{122}Te(d,n)$ reaction with 95.4 % enriched Te target. The impurity caused in ^{123}I by the latter method was reported to be 0.09 %, 0.04 %, 0.86 %, and 0.09 % for ^{124}I, ^{126}I, ^{130}I, and ^{131}I respectively. There is also a report which have announced no impurity was found except 1 % of ^{131}I by using the $^{127}I(d,6n)$ reaction. The $^{nat}Sb(\alpha,xn)^{123}I$ reaction was reported to be 0.69 for ^{124}I, and $^{nat}Sb(^{3}He,xn)^{123}I$ reaction also was reported to be 0.69 % for ^{124}I and to be 0.3 %, 0.8 % , and 4.1 % for ^{124}I, ^{125}I, and ^{121}I, respectively. In thess case there is no need of using enriched isotope. In conclusion $^{122}Te(d,n)^{123}I$ and $^{124}Te(p,2n)^{123}I$ are the most promissing reactions for minimum impurity in ^{123}I reported so far.

Calculated excitation functions; We present comparison between experimental excitation functions and results calculated with ALICE[11]. In Fig. 7, we show proton excitation function on ^{127}I target.

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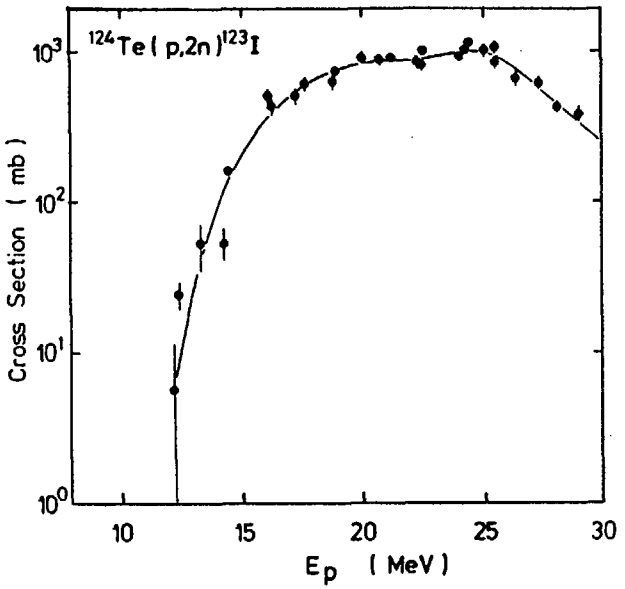

Fig. 1 Excitation function of ^{123}Te(p,2n)^{123}I on 99.87 % and 91.86 % isotopic enrichment of ^{124} (Ref.1).

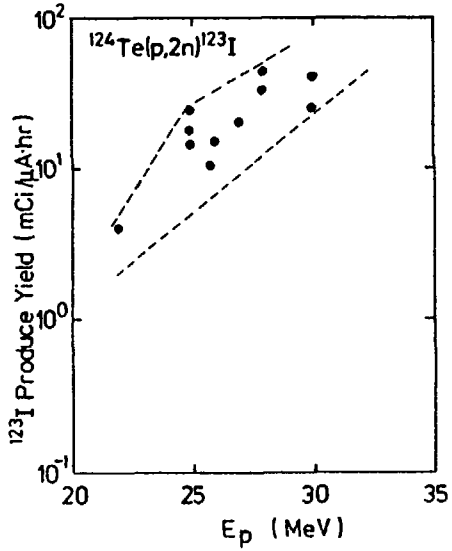

Fig. 2 Practical yield of ^{123}I by ^{124}Te(p,2n)^{123}I reaction.

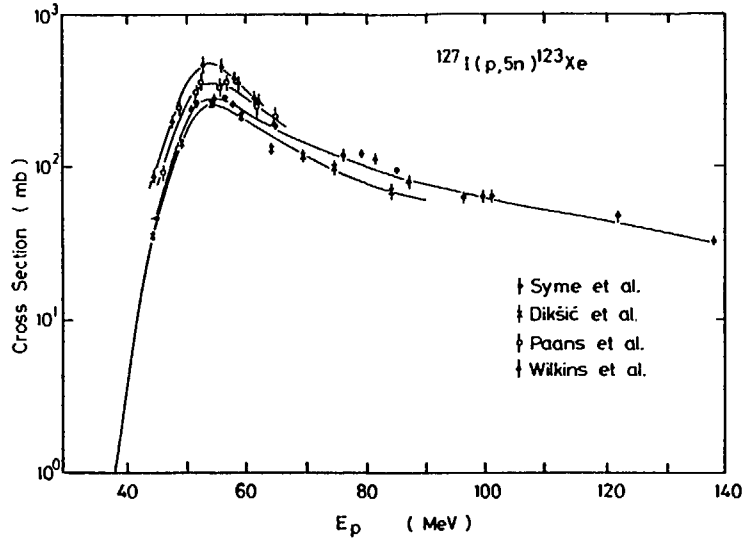

Fig. 3 Comparision of excitation functions of $^{127}I(p,5n)^{123}Xe$ reaction (Refs.2-5).

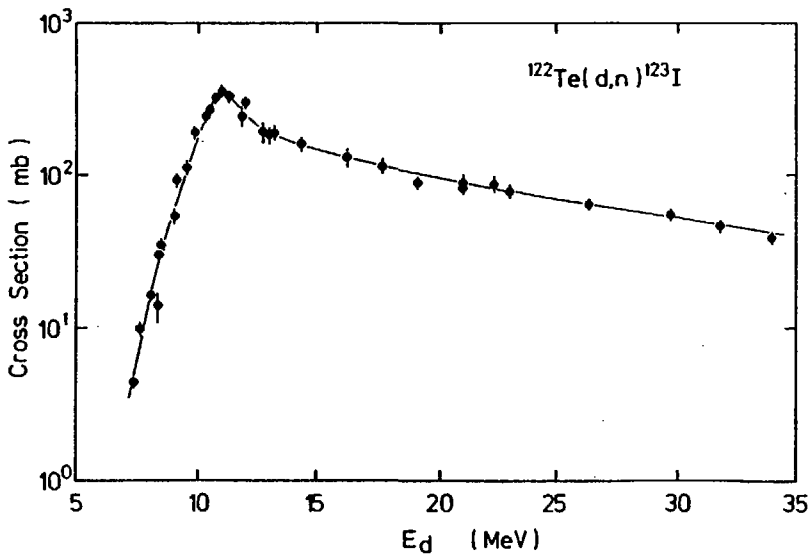

Fig. 4 Excitation function of $^{122}Te(d,n)^{123}I$ reaction (Ref.6).

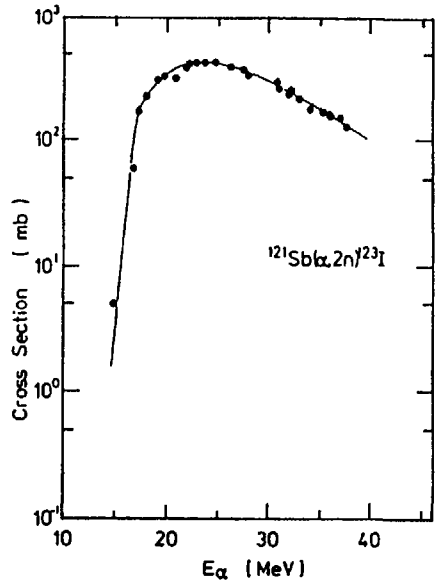

Fig. 5 Excitation function of $^{nat}Sb(\alpha,xn)^{123}I$ reaction (Ref.9).

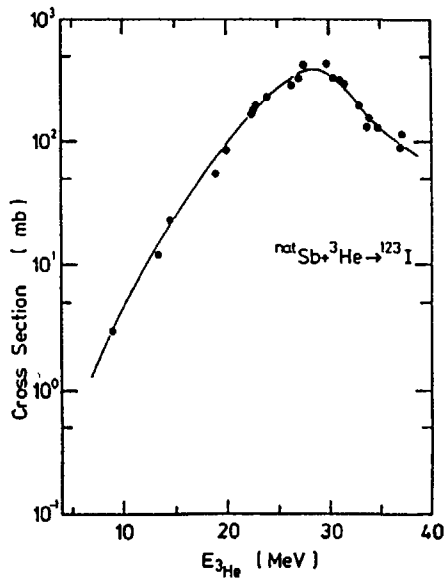

Fig. 6 Excitation function of $^{nat}Sb(^3He,xn)^{123}I$ reaction (Ref.9).

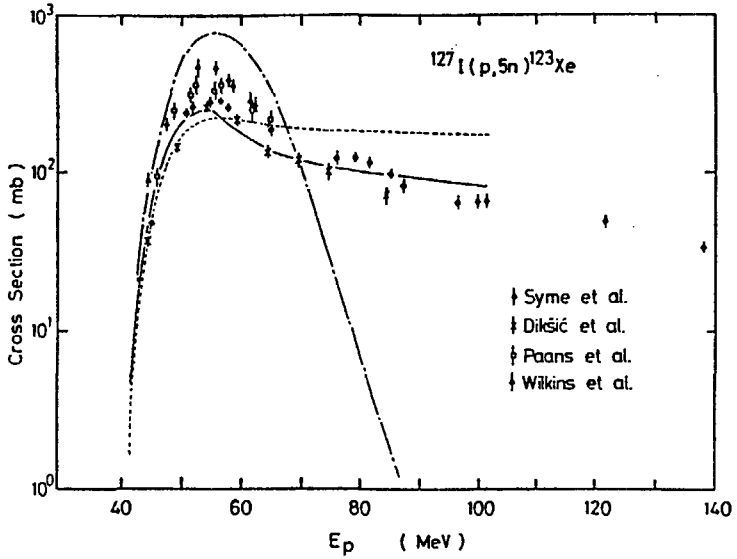

Fig. 7 Calculated (ALICE) and experimental excitation functions for proton induced reaction on ^{127}I target. Dot-dashed line is CN-Theory, and Dashed and solid lines are hybrid model.

Post-meeting contributation

Measurement of the Cyclotron Beam Energy of the Alpha Particles by Rutherford Scattering in Gold Foil†

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ABSTRACT

An example of the measurement of the alpha particle energy of a cyclotron by the Rutherford scattering technique in gold foil is discussed.

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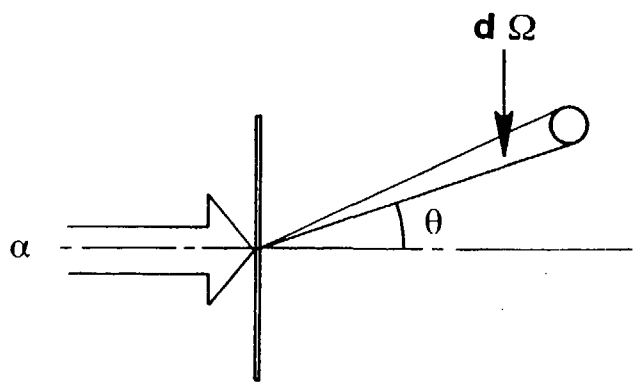
INTRODUCTION

A convenient measurement of the particle beam energies of cyclotrons used for medical radioisotope production would permit standardization at hospital-based cyclotrons.

At sufficiently low beam energies ($\leq$ 50 MeV), alpha particles can be stopped in a solid stated detector to achieve accurate energy measurements. To use this technique, it is necessary to reduce beam intensity significantly, and this is best accomplished by Rutherford scattering (1) from a thin, high-Z foil through a large angle. The foil of the scatterer is so thin that the alpha particles pass completely through with only a small decrease in their velocity. However, in the process of traversing the foil, each alpha particle experiences many small deflections due to Columb force acting betweeen its charge and the positive and negative charges of the atoms of the foil.



The frequency of the low-energy scattering process, due to Columb forces, is governed by well known Rutherford scattering formulas. If the mass M_1 of the incident charge particles (alpha) is small compared with the mass of the scatterer nucleus M_2 (^{197}Au), at the laboratory coordinate system the differential cross section for scattering into solid angle $d\Omega$ with no change of velocity v is

$$(1) \qquad d\sigma(\phi) = \frac{b^2}{16} \cdot \frac{1}{\sin^4(\phi/2)} \cdot d\Omega$$

in which

$$(2) \qquad b = \frac{zZe^2}{\frac{1}{2}M_1v^2}$$

where $E=\frac{1}{2}M_1v^2$ is the kinetic energy of the incident particle, ϕ is the angle of scattering from the incident direction, and ze and Ze are the charges of the two particles, respectively. Multiplying this cross section by the number of nuclei per square centimeters of the scatterer material gives the fraction scattered into solid angle $d\Omega$ at the scattering angle ϕ. At the distance r from the scattering point, the number of the alpha particles, $N(\phi, r)$ falling on a unit area is given

$$(3) \qquad \frac{N(\phi,r)}{N_0} = \frac{1}{16}(\rho.t)\left(\frac{zZe^2}{\frac{1}{2}M_1v^2}\right)^2 \left(\frac{1}{\sin^4(\phi/2)}\right)\left(\frac{A}{r^2}\right)$$

where the quantity N_0 is the number of alpha particles incident on the foil of thickness t and density ρ (nuclei per cm^3); A is the surface area of the detector. Equation (3) predicts that the number of scattered alpha particles is inversely proportional to the cube of the half scattering angle, ϕ.

Example: For 1 μA of 28 MeV particles, incident upon 10 μg/cm^2 of gold foil at various scattering angle the number of events at a detector (1 cm^2 surface area) placed at 20 cm from scattering points are as follows:

$z = 2$, $Z = 79$, $e = 4.8 \times 10^{-10}$ esu

$$b = \frac{zZe^2}{E} \qquad \frac{(2)(79)(4.8 \times 10^{-10}\ \text{esu})^2}{(28\ \text{MeV})(1.602 \times 10^{-6}\ \text{erg.MeV}^{-1})} = 8.12 \times 10^{-13}$$

$$\frac{b^2}{16} = 4.12 \times 10^{-26}$$

$$\rho.t = (10^{-5}\ \text{g.cm}^{-2})\ \frac{(6.023 \times 10^{23}\ \text{atoms.mole}^{-1})}{197.97\ \text{g.mole}^{-1}} = 3.06 \times 10^{16}\ \text{atoms.cm}^{-2}$$

$$d\Omega = \frac{A}{r^2} = \frac{1\ \text{cm}^2}{(20\ \text{cm})^2} = \frac{1}{400}$$

therefore:

$$\text{Fraction scattered;}\quad \frac{N(\phi,r)}{N_0} =$$

$$(4.12 \times 10^{-26})(3.06 \times 10^{16}\ \text{atoms.cm}^{-2})\ (\frac{1}{400})(\frac{1}{\sin^4(\phi/2)}) =$$

$$3.15 \times 10^{-12}\ \ (\frac{1}{\sin^4(\phi/2)})$$

For 1 A of alphas, there are 3.13×10^{12} particles per second therefore; the number of scattered alphas per second;

$$N(\phi,r) = 9.87 \times \frac{1}{\sin^4(\phi/2).}$$

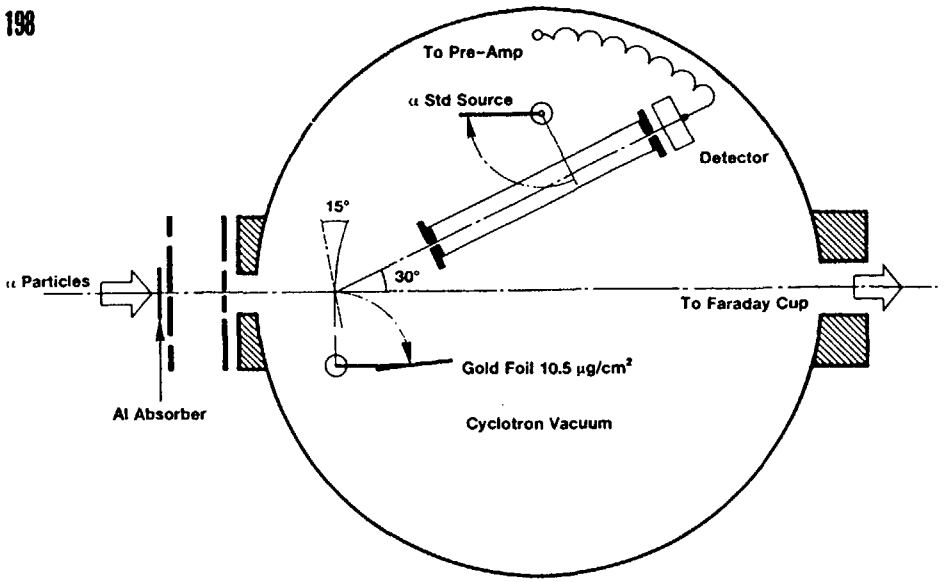
The results are tabulated in Table 1.

Table 1: Number of scattered alpha particles in solid angle $d\Omega$ as a function of scattering angle, ϕ.

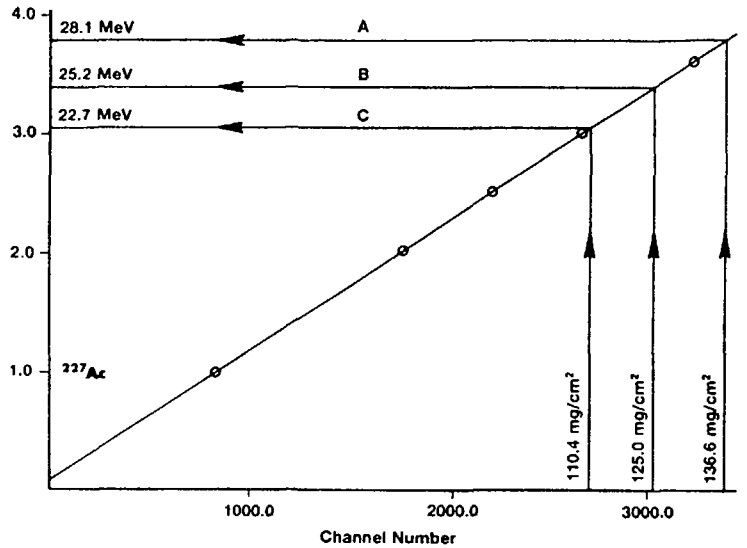
ϕ, deg	$\frac{N(\phi,r)}{N_0}$	$N(\phi,r)$
10	5.46×10^{-8}	1.71×10^5
15	1.09×10^{-8}	3.40×10^4
20	3.46×10^{-9}	1.08×10^4
25	1.44×10^{-9}	4.49×10^3
30	7.02×10^{-10}	2.20×10^3

RESULTS AND DISCUSSION

The scattering chamber which was used for this demonstration is shown in Figure 1. After degradation of the α energy from 46 MeV (the energy which is available at the Brookhaven National Laboratory 60" cyclotron) to 28 MeV in Al, the α particles were collimated into a narrow parallel beam by two collimators (3 mm in diameter), and were deflected in 10.5 μg.cm^{-2} of Au foil. The deflected α-particles were completely stopped in a 500 micon-thick Au-Si surface barrier detector placed at a 30° angle with respect to the direction of the alpha beam. The energy calibration (in the 7.38-30.73 MeV region) was performed utilizing a digital pulse generator. The 7.38 MeV α particle from a ^{227}Ac source was used as the first point in calibration curve. This calibration was also performed while the beam of cyclotron was on. To do these measurements, the Au foil was turned away from the beam path and the ^{227}Ac source was placed in front of the detector. The integrity of the detector calibration was confirmed. Then the beam was intercepted, and without opening the scattering chamber, the Au foil was carefuly turned back into the beam path and the ^{227}Ac source was removed from the face of the detector.



(1) Schematic of the Rutherford Scattering Chamber used for measurement of alpha particle energy.



(2) Calibration of the cyclotron alpha particle energy with the response relative to the 7.386 MeV alpha's of ^{227}Ac. The slope is 8.21 x 10^{-3} MeV per channel.

A typical standard curve and the results from three separate measurements in ploying 110.4, 125.0 and 136.0 mg/cm^2 of Al degrader are shown in Figure 2. The average value of the energy from these measurements were 43.6 $\pm$ 2.0 MeV which is 2.4 MeV lower than what was calculated from magnetic field strength and the radius of the cyclotron.

We conclude that the Rutherford scattering technique is a convenient and inexpensive method for verification of the alpha particle energy of cyclotrons utilized for medical radioisotope production. The earlier measurements reported by this laboratory (2) for the $^{209}Bi(d,2n)^{211}At$ excitation function gave results in agreement with other laboratories. However, the data reported by this laboratory (3) for the Ge(He,2n)Se excitation functions is transposed to higher energy than reported by Nozaki et.al. (4) although agreement in the magnitude of the cross section is consistent between the two laboratories. We feel this discrepancy is probably due to use of the cyclotron beam energy calculated from the operating characteristics of the BNL "60" cyclotron.

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