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Summary Report of the Second Research Co-ordination Meeting on DEVELOPMENT OF REFERENCE CHARGED-PARTICLE CROSS SECTION DATABASE FOR MEDICAL RADIOISOTOPE PRODUCTION

National Accelerator Centre, Faure, Cape Town, South Africa
7 to 10 April 1997

Prepared by

Pavel OBLOŽINSKÝ
IAEA Nuclear Data Section
Vienna, Austria

October 1997

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

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Abstract

The present report contains the summary of the 2nd Research Co-ordination Meeting on "Development of Reference Charged-Particle Cross Section Database for Medical Radioisotope Production", held at the National Accelerator Centre at Faure, near Cape Town, South Africa, from 7 to 10 April 1997. An outline of the TECDOC, summarizing the results of the project, is presented. Details are given on recommendations for proton induced reactions, and on the work plan for the second part of the project.

October 1997

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1 Summary of the Meeting

Objectives and Participation

The 2nd Research Co-ordination Meeting (RCM) on "Development of Reference Charged-Particle Cross Section Database for Medical Radioisotope Production" was held at the National Accelerator Centre at Faure, near Cape Town, South Africa, from 7 to 10 April 1997. The local host of the RCM was F.M. Nortier.

The purpose of the meeting was to review the progress achieved in developing the reference charged-particle database for medical radioisotope production, to review tasks and co-ordination procedures agreed upon at the 1st Research Co-ordination Meeting and to formulate priorities and tasks for further work. T.F. Tárkányi of the Institute of Nuclear Research at the Hungarian Academy of Sciences (ATOMKI), Debrecen, Hungary served as a chairman of the Meeting. The detailed Agenda is attached (Appendix 1) along with the extended abstracts of the progress reports (Appendix 2).

The meeting was attended by the representatives of 6 laboratories participating in the project, and by 2 cost-free observers. The participating laboratories were represented by A. Hermanne (Vrije Universiteit Brussel, Brussels, Belgium), Zhuang Youxiang (China Institute of Atomic Energy, Beijing, China), B. Scholten (Forschungszentrum Jülich GmbH, Jülich, Germany), T.F. Tárkányi (Hungarian Academy of Sciences, Debrecen, Hungary), Y. Shubin (Institute of Physics and Power Engineering, Obninsk, Russia), and F.M. Nortier (National Accelerator Centre, Faure, South Africa). Furthermore, R.M. Lambrecht (Eberhard-Karls Universität Tübingen, Tübingen, Germany), I.W. Schroeder (National Accelerator Centre, Faure, South Africa) and H. Vera Ruiz (IAEA Vienna) attended as observers. For details see Appendix 3.

A useful common session was held with the adjacent Consultants' Meeting on "Production Technologies for ^{99}Mo and ^{99m}Tc" (Scientific Secretary H. Vera Ruiz, IAEA Vienna).

Main Conclusions

It was concluded that the CRP is making a satisfactory progress and the goals initially defined will be met by the end of 1998. Particularly, the evaluation of 14 proton-induced reactions, identified as top priority for the first part of the CRP, is nearing the completion. As planned, the second part of the CRP will focus on further 26 reactions, including those induced by deuterons, ^{3}He and alphas. The detailed list of tasks for future work can be found in Chapters 4 and 5 of the present Summary Report.

TECDOC on Development of Reference Charged-Particle Cross Section Database for Medical Radioisotope Production will be prepared as the main result of the present CRP. Its draft should be ready by September 1998.

The last Research Co-ordination Meeting should be held in October 1998 in Brussels. A. Hermanne kindly offered his services as a host of the Meeting.

2 Progress Reports and Presentations

Six participating laboratories presented their progress reports at the meeting. The report of M.G. Mustafa and M. Blann (LLNL, Livermore, U.S.A.), who were unable to participate at the meeting, was submitted in writing. See Appendix 2 for more details on these progress reports.

In addition, R. Lambrecht (Eberhard-Karls-Universität Tübingen, Tübingen, Germany) presented a short work-in-progress report considering the ^{103}Rh(α,2n)^{105}Ag nuclear reaction as a potential monitor reaction applicable to activation analysis of geochemical materials. Although the reaction is outside the scope of the 2nd RCM, Y. Shubin agreed to collaborate with theoretical input concerning the experimental measurements of the excitation functions of ^{103}Rh(α,xn)$^{107-x}$Ag and ^{103}Rh(^{3}He,xn)$^{106-x}$Ag (where x = 2,3).

The work done by K. Gul (Islamabad, Pakistan) in support of the present CRP was noted. In particular he has carried out calculations for the excitation functions of ^{63}Cu(p,n)^{63}Zn, ^{63}Cu(p,2n)^{62}Zn and ^{65}Cu(p,n)^{65}Zn reactions in the 3-25 MeV energy range, and for ^{63}Cu(α,n)^{66}Ga, ^{63}Cu(α,2n)^{65}Ga, ^{63}Cu(α,n+p)^{65}Zn, ^{65}Cu(α,n)^{68}Ga and ^{65}Cu(α,2n)^{67}Ga reactions in the 8-25 MeV energy range using statistical and preequlibrium nuclear reaction models. These calculations have been compared with reported measurements. For details see Report INDC(PAK)-13 (IAEA, Vienna, June 1997).

H. Vera Ruiz pointed out the importance of cross section evaluations including measurements for cyclotron production trigered by the increased role of therapeutic applications. Particularly, he mentioned the production of β^- emitters such as ^{153}Sm, ^{186,188}Re, and also ^{166}Ho and ^{165}Dy. These data would be of value for countries without reactors but possessing cyclotrons or in applications where highest specific activities are required.

3 TECDOC on Reference Charged-Particle Cross Section Database for Medical Radioisotope Production

The outline of the IAEA Technical Document (TECDOC) on Development of Reference Charged-Particle Cross Section Database for Medical Radioisotope Production was discussed in detail. The total length of TECDOC should be limited to about 150 pages, possibly with the attached CD ROM containing the data file. The detailed outline is given below, responsible CRP participants are indicated in brackets. Also summarized are procedures and formats.

3.1 Outline

Pages

Executive Summary (Obložinský) 2

Chapter 1. Introduction (Qaim, Tárkányi) 8
- 1.1 Data needs
- 1.2 Reactions studied
- 1.3 Overview of present TECDOC

Chapter 2. Experimental evaluation (Tárkányi, Hermanne) 30
- 2.1 New measurements
- 2.2 Compilation
- 2.3 Analysis and selection of experimental data
- 2.4 Methods of fitting
- 2.5 Comparison of fits to experimental data
- 2.6 Systematics of experimental data (Zhuang)

Chapter 3. Theoretical evaluation (Shubin, Zhuang, Mustafa) 40
- 3.1 Nuclear reaction models
- 3.2 Codes and calculations
- 3.3 Comparison of all calculations with selected experimental data

Chapter 4. Reference cross section database: excitation functions (Hermanne) 15
- 4.1 Recommendations
- 4.2 Beam monitor reactions
  - Protons (7 reactions)
  - Deuterons (4 reactions)
  - ^{3}He (5 reactions)
  - Alphas (5 reactions)
- 4.3 Gamma emitters
  - (11 reactions)
- 4.4 Positron emitters
  - (8 reactions)
- 4.5 Unresolved cases

Pages

Chapter 5. Validation of data (Nortier, input Hermanne, Scholten, Tárkányi) 10
- 5.1 Intercomparison of monitor reactions
- 5.2 Integral experiments
- 5.3 Comparison of evaluated data with integral experiments

Chapter 6. Yields for production reactions (Tárkányi) 5

Attachment: Guidance to measurers and users of data (Qaim, Nortier, Tárkányi) 30
1. Guidance to measurers
2. Guidance to users

Total: 150 pages

Notes

Chapter 2: Responsible for 2.4 and 2.5 is Hermanne. Produced will be figures for all reactions including fits whenever avialable. Input to 2.4 and 2.5 will come from Shubin, Zhuang and, if possible, also from Scholten. Responsible for 2.6 is Zhuang.

It was noted that it may be appropriate to publish, in addition to the chapter 2 of the TECDOC, three more detailed reports (one each on Monitor Reactions, γ-Ray Emitters and Position Emitters).

Chapter 3: Figures will be included in 3.3 for all reactions.

Chapter 4: Tables will be prepared in 0.5 MeV steps. In addition to numerical data, analytical fits will also be given (Scholten). It is understood that this chapter can be completed only after all the evaluations have been made available and discussed thoroughly by the CRP.

Chapter 5: 5.2, 5.3 only γ- and positron emitters. No data will be available before the chapter is to be prepared.

Chapter 6: It is understood that this chapter can be completed only after all the evaluations have been made available and discusseed thoroughly by the CRP.

3.2 Procedures and Formats

1. *Format of contributions*
   - Text: MS Word 6.0 (strongly preferred) or ASCII
   - Graphs: Excel 5.0 and hardcopy
   - Tables: Excel 5.0 (strongly preferred) or ASCII

2. *Deadlines*
   - Contributions: February 1998
   - Chapters: May 1998
   - Complete draft: September 1998

3. *Responsibilities*
   - Contributions: All
   - Chapters: As indicated
   - Complete draft: Qaim and Tárkányi

4. *Format of numerical database*

   The ENDF-6 format was recommended with the understanding that detailed specifications must still be agreed upon. It was noted that the actual implementation of the format is under discussion in the Subgroup 13 (Nuclear Data for Intermediate Energies under the OECD NEA Working Party). In view of this it was recommended to adopt the same format specifications as will be agreed upon in the Subgroup 13.

4 Recommendations for Proton-Induced Reactions

The evaluation of the excitation functions for proton-induced reactions, constituting the first part of the present CRP, was discussed in detail The list of these reactions includes 7 reactions for beam monitoring and 7 reactions for the production of gamma emitters.

4.1 Adopted Evaluation Procedure

The evaluation procedure adopted for the above-mentioned reactions was the following:

- The existing experimental data were collected by the experimental groups (Jülich, Brussels, Debrecen and partly Faure) and were critically analysed.

  In about 50% of the cases a selection of the data was performed, taking into account deficiencies of the measurements such as possible errors in beam current measurement, unreliable nuclear data and unexplainable large deviation from the bulk of other measurements or from a general trend in the excitation functions.

- Calculations were performed by three theoretical groups (Livermore, Obninsk and in several cases by Beijing), using different versions of the ALICE code. These calculations were then compared with the (selected) experimental data.

- To some extent the curves obtained by means of the systematics of experimental data (Beijing) were considered.

- Recommended data were obtained after a round table discussion of each individual reaction at the present meeting. Considered were the three approaches mentioned above, taking into account amongst others the shape of the excitation function, the magnitude and position of the maximum, the quality of the experimental data and the mass region of the target nuclei.

- If the shape of the excitation function and the position of the maximum are in agreement and when theoretical values and experimental data agree well, theoretical calculations will be used to generate the recommended values.

- If only the magnitude of the maximum is different, a scaling of the theoretical values will be applied.

- When the deviation between theoretical values and experimental data is too large and includes differences in shape, position and value of the maximum, a fitting of the selected experimental data series will be performed to yield the recommended values.

- The procedure as outlined above was not applicable to all cases. Additional specific solutions were therefore proposed:

  - in one case the systematics approach was proposed for generating the final values,
  - in some cases a more thorough analysis and selection of experimental data has to be made before theoretical scaling can be applied, and
  - for one reaction new experimental data have to be obtained.

4.2 Beam Monitors

$^{nat}Ti(p,x)^{48}V$

There is a problem with theoretical calculations (both Livermore and Obninsk - too high cross sections at low energies). It was recommended to have the reaction cross section near the maximum (13-11 MeV) remeasured by 3 experimental groups (Brussels, Debrecen, Jülich, deadline 1 September 1997). A new selection of experimental data will be done by Tárkányi. Then, Obninsk will do careful calculations with STAPRE. It is also recommended to fit the selected set of experimental data (Beijing, Obninsk).

$^{nat}Ni(p,x)^{57}Ni$

Theoretical calculations (Obninsk) were found to be in a reasonable agreement with experimental data. However, contributions from other Ni isotopes at high incident energies should be included and smaller energy steps should be applied at low energies. It was recommended that Obninsk will perform new calculations, these new results will be accepted up to 50 MeV. No recommendation will be given for higher incident energies.

$^{nat}Cu(p,x)^{56}Co$

There is a serious problem with theoretical calculations due to level densities. Obninsk will do careful recalculation, looking into the level density problem. It is expected that Livermore will also perform this calculation. It was further recommended to perform a critical analysis of experimental data (Faure, deadline 1 October 1997). Also recommended was to make a fit to experimental data by two different approaches (Beijing and Obninsk).

$^{nat}Al(p,x)^{22}Na$

The same conclusions apply as in the case of $^{nat}Cu(p,x)^{56}Co$.

$^{nat}Cu(p,x)^{62}Zn$

Theoretical results (Obninsk) appear to be fairly good and they could be accepted. However, it was felt that preference should be given to the fit of experimental data (selection and fitting to be done by Jülich, deadline end of 1997).

$^{nat}Cu(p,x)^{63}Zn$

There is a certain problem with the theoretical results from Obninsk (about 10% discrepancy with experimental data just below the peak). It was recommended to accept the experimental fit (to be done by Jülich, using selected experimental values, deadline end of 1997).

$^{nat}Cu(p,x)^{65}Zn$

There are certain problems with the theoretical results just beyond the peak. As in the above-mentioned case, it was recommended that Jülich will perform a fit to the experimental data which will then be accepted. If Scholten is not able to have the fitting procedure performed (response date 1 July 1997), the fit to the selected experimental data will be done by Obninsk and Beijing.

4.3 Gamma Emitters

$^{111}Cd(p,n)^{111}In$

It was recommended to accept the theoretical results from Obninsk, but Obninsk should do new calculations with smaller energy steps around the peak. It was further recommended that Beijing will perform a fit to the experimental data (deadline end of 1997).

$^{112}Cd(p,2n)^{111}In$

After a long discussion it was preliminary recommended to accept the results from the systematics provided by Beijing. It was decided that it would be useful to resolve the 10% inconsistency between Obninsk's calculations and experimental data at the peak by performing new cross section measurements (Brussels and Debrecen).

$^{nat}Cd(p,x)^{111}In$

It was recommended to accept the experimental data by Faure. An analytical fit to Nortier's data will be done by Jülich.

$^{203}Tl(p,3n)^{201}Pb$

After a very long discussion it was recommended to accept the theoretical results from Obninsk. However, only data up to 35 MeV should be considered in view of the production of contaminants at higher energies.

$^{123}Te(p,n)^{123}I$

It was recommended that the theoretical results from Obninsk are accepted. However, Obninsk should rescale its curve to reproduce the experimental peak value based on data of Scholten and Mahunka (recommended experimental peak value to be provided by Debrecen).

$^{124}Te(p,2n)^{123}I$

It was recommended to accept the theoretical results of Obninsk after rescaling the curve so that the recommended experimental peak value is reproduced. This latter value will be deduced by Debrecen from the experimental data of Scholten and Kondo.

$^{127}I(p,5n)^{123}Xe$

It was recommended that Faure will perform a critical analysis of the compiled experimental data. Then, Obninsk will rescale its theoretical curve to reproduce the recommended experimental peak value to be provided by Faure. It was recommended that this rescaled curve is accepted.

5 Work Plan for New Reactions

In addition to finalizing the evaluations of the 14 proton-induced reactions as discussed above, the following work plan for the next 18 months has been agreed upon:

5.1 Data Compilation and Analysis

All the reactions mentioned in the first summary report will be investigated and the following division of responsibilities was accepted:

A. Monitor reactions

Debrecen: Monitor reactions for deuterons
$^{nat}Al(d,x)^{22}Na$
$^{nat}Ti(d,x)^{48}V$
$^{nat}Fe(d,x)^{56}Co$
$^{nat}Ni(d,x)^{61}Cu$

Debrecen: Monitor reactions for ^{3}He particles
$^{nat}Al(^{3}He,x)^{22}Na$
$^{nat}Ti(^{3}He,x)^{48}V$
$^{nat}Cu(^{3}He,x)^{66,67}Ga,^{65}Zn$

Debrecen: Monitor reactions for α particles
$^{nat}Al(\alpha,x)^{22}Na$
$^{nat}Ti(\alpha,x)^{51}Cr$
$^{nat}Cu(\alpha,x)^{66,67}Ga,^{65}Zn$

B. Excitation functions for γ-emitters

Debrecen:	$^{67}Zn(p,n)^{67}Ga$ $^{68}Zn(p,2n)^{67}Ga$
Brussels:	$^{209}Bi(\alpha,2n)^{211}At$ (not a priority)
Faure:	$^{nat}Kr(p,x)^{81}Rb$ $^{82}Kr(p,2n)^{81}Rb$

C. Excitation functions for positron emitters

Jülich:	$^{14}N(p,\alpha)^{11}C$ $^{16}O(p,\alpha)^{13}N$ $^{14}N(d,n)^{15}O$ $^{18}O(p,n)^{18}F$ $^{20}Ne(d,\alpha)^{18}F$
Brussels:	$^{69}Ga(p,2n)^{68}Ge$ (not a priority) $^{nat}Ga(p,x)^{68}Ge$ (not a priority)
Faure:	$^{85}Rb(p,4n)^{82}Sr$ $^{nat}Rb(p,x)^{82}Sr$

D. Procedures

The following procedures were approved:

1. The experimental groups, as indicated in the above-mentioned list, have to compile and critically analyse the experimental data and make a selection.

   The available data should be screened and, if possible, corrected for errors and shortcomings.

2. T.F. Tárkányi will act as co-ordinator for the experimental groups and has to supply the finally selected experimental data to Obninsk, Beijing, Livermore and to S. Gul (Pakistan) for theoretical evaluation.

3. All data (with clear indication of selected sub-set) have to be sent to Debrecen before 20 December 1997 in EXCEL 5.0 format (according to the Debrecen outlay).

   Upon request copies of publications not available in Debrecen have to be sent to the co-ordinator.

5.2 Calculations

The following procedures were approved:

1. The co-ordinator (T.F. Tárkányi) will send the experimental data files to the theoretical evaluators before 31 January 1998.

2. The following calculations will be performed for 26 priority reactions listed in 5.1:

   - Beijing
     1) SPEC or CUNF code calculations (EXCITON model) for all reactions.
     2) Weighted fit of selected data for all reactions.

   - Obninsk
     1) ALICE-IPPE code calculations for all reactions.
     2) Weighted fit (PADE approximation) for selected data for all reactions where the method is applicable.

   - Livermore
     1) ALICE HMS code calculation for all reactions.

3. Results of calculations have to be sent to the Scientific Secretary (P. Obložinský) before 1 July 1998.

4. The Scientific Secretary will distribute the results of the calculations to all participants before 1 August 1998.

5.3 Experimental Measurements

A. Cross section measurements

1. Debrecen and Brussels will complete additional measurements on $^{68}Zn(p,2n)^{67}Ga$ before 1 December 1997.

2. Jülich and Debrecen will do more detailed measurements on the $^{18}O(p,n)^{18}F$ reaction up to 20 MeV and complete the work.

3. Jülich, Debrecen and Brussels will independently (3 separate experiments) remeasure the $^{nat}Ti(p,x)^{48}V$ cross sections with several foils in a stack at an incident proton energy slightly above the maximum. The beam current will be measured using a Faraday cup and the $^{nat}Cu(p,x)^{65}Zn$ reaction as monitor (Kopecky data). This is to be completed before 1 December 1997.

4. Brussels and Debrecen volunteered to remeasure $^{nat}Cu(\alpha,x)$ reactions up to 40 MeV before 1 December 1997.

5. Intercomparison of monitor reactions: Jülich, Brussels and Debrecen may perform several irradiations of mixed stacks at selected energy points of materials considered for monitor reactions for the p, d, α, and ^{3}He reactions. Cross sections should be determined by a Faraday cup measurement of the integrated charge. A higher energy irradiation with 66 MeV protons on Al and Cu may be performed at Faure.

6. Debrecen and Brussels will perform additional measurements on $^{112}Cd(p,2n)^{111}In$ before 1 May 1998. Problems with the availability of the enriched material may rise.

B. Integral measurements

Integral measurements are needed for validation of the microscopical data. In the limits of availability of enriched material and technology to produce thick targets (energy loss about 5 MeV or more) the experimental laboratories offer to perform the following irradiations (for at least 1 energy) and yield determinations:

-	$^{67}Zn(p,n)^{67}Ga$	Debrecen
	$^{111}Cd(p,n)^{111}In$	
	$^{123}Te(p,n)^{123}I$	
-	$^{68}Zn(p,2n)^{67}Ga$	Brussels and Debrecen
-	$^{203}Tl(p,3n)^{203}Pb$	Brussels
-	$^{nat}Rb(p,x)^{82}Sr$	Faure
-	$^{124}Te(p,2n)^{123}I$	Jülich
-	$^{127}I(p,5n)$	Faure

If possible, the integral measurements should be completed by 1 September 1998.

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Appendix 1

IN REPLY PLEASE REFER TO:
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2nd Research Co-ordination Meeting on

"Development of Reference Charged-Particle Cross Section Database for Medical Radioisotope Production"

National Accelerator Centre
Faure/Cape Town, South Africa
7-10 April 1997

A G E N D A

Monday, 7 April

09:30-10:00 Opening

- Opening Address Prof. J.F. Scharpey-Schafer (Director, NAC), Pavel Obložinský (IAEA)
- Election of Chairman
- Adoption of Agenda
- Announcements

10:00-13:00 Review

- Review of Actions from the 1st Meeting
- Outline of the IAEA TECDOC on Reference Charged-Particle Cross Section Database for Medical Radioisotope Production
- Progress Reports by the CRP Participants
  - A. Hermanne (Brussels)
  - M. Nortier (Faure)
  - B. Scholten (Jülich)
  - Yu. Shubin (Obninsk)
  - T.F. Tárkányi (Debrecen)
  - Zhuang Youxiang (Beijing)

Notes: *Each report should be confined to about 20'. Reporters should concentrate on overview of activities, details should be left to later discussion on each specific reaction.*
Each reporter should bring with him a written summary (1-2 pages) of the work done and, if possible, also a copy of the full report.

13:00-14:00 Lunch

14:00-15:00 Review continued

- Status of experimental measurements (Debrecen, Brussels, Jülich)
  - ^{48}V, ^{67}Ga, ^{18}F
  - Ni+p (secondary n effect) Comment: Not on the original list
  - Ni+d, Cu+d, Fe+d Comment: Not on the original list

15:00-18:00 Evaluations

- Evaluation of monitor excitation functions
  (discussion leader T.F. Tárkányi)

  Note: Reactions to be discussed
  - $^{nat}Ti(p,x)^{48}V$
  - $^{nat}Ni(p,x)^{57}Ni$
  - $^{nat}Cu(p,x)^{62}Zn$
  - $^{nat}Cu(p,x)^{63}Zn$
  - $^{nat}Cu(p,x)^{65}Zn$
  - $^{nat}Cu(p,x)^{56}Co$
  - $^{nat}Al(p,x)^{22}Na$

  a. Experimental evaluations
     (input Debrecen, Brussels, Jülich, Faure)
  b. Theoretical evaluations
     (input Beijing, Obninsk, Livermore)

<u>**Tuesday, 8 April**</u>

09:00-13:00 Evaluations continued

- Evaluation of monitor excitation functions, continued
- Evaluation of excitation functions for γ-emitters
  (discussion leader A. Hermanne)

  Note: Reactions to be discussed
  - $^{111}Cd(p,n)^{111}In$
  - $^{112}Cd(p,2n)^{111}In$
  - $^{nat}Cd(p,x)^{111}In$
  - $^{203}Tl(p,3n)^{201}Pb{\rightarrow}^{201}Tl$
  - $^{124}Te(p,2n)^{123}I$
  - $^{123}Te(p,n)^{123}I$ *Comment: Not on the original list*
  - $^{127}I(p,5n)^{123}Xe{\rightarrow}^{123}I$

  a. Experimental evaluations
     (input Debrecen, Brussels, Jülich, Faure)
  b. Theoretical evaluations
     (input Beijing, Obninsk, Livermore)

13:00-14:00 Lunch

14:00-18:00 Evaluations continued

<u>**Wednesday, 9 April**</u>

09:00-11:00 Discussion

- General discussion
- Progress in evaluation methodology
  a. Experimental procedures
     (discussion leader T.F. Tárkányi)
  b. Theoretical procedures
     (discussion leader Yu. Shubin)

11:00-13:00 Future

- Future work plan

Note: Proposed responsibilities for new compilations

- *Monitor reactions: Debrecen, Faure*
- *^{67}Ga: Debrecen*
- *^{68}Ge/^{68}Ga: Brussels*
- *^{81}Rb(^{81}Kr), ^{82}Sr: Faure*
- *^{11}C, ^{13}N, ^{15}O, ^{18}F: Jülich*

a. Monitor reactions with d, ^{3}He and ^{4}He
(discussion leader T.F. Tárkányi)
- Short contribution by R.M. Lambrecht: ^{103}Rh(α,2n)^{105}Ag

b. Further γ-emitters
(discussion leader A. Hermanne)

c. Positron emitters
(discussion leader B. Scholten)

d. Experimental measurements
(discussion leader M. Nortier)
- Uncompleted measurements for ^{67}Ga, ^{18}F
- Integral tests of evaluated data

13:00-14:00 Lunch

14:00-18:00 Report

- Drafting of the meeting summary report
- Guidelines for measurements and use of nuclear data (T.F. Tárkányi)
- Publication policy

Thursday, 10 April

09:00-13:00 Report continued

- Adoption of the meeting summary report
- Final discussion

13:00-14:00 Lunch

14:00-17:00 Common Session

- Common session with CM "Production Technologies for ^{99}Mo and ^{99m}Tc"

Note: *Participation is optional. Discussed will be the cyclotron technologies. Lectures will be given by R.M. Lambrecht (Germany), T.F. Tárkányi (Hungary) and M. Lagunas-Solar (U.S.A.). The summary of our meeting will be given by P. Obložinský (IAEA).*

17:00-19:00 Tour to the NAC laboratories

19:00-20:00 Reception and Adjournment

Appendix 2

EXTENDED ABSTRACTS OF THE PROGRESS REPORTS

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Progress Report of the VUB Cyclotron group Brussels - Belgium
Prof. A. Hermanne

The different results obtained between october 1995 and march 1997 in the frame of research on charged particle cross sections of nuclear reactions used for beam monitoring and production of medically relevant radionuclides are summarised here.

1.Tasks devoted to the Brussels group at the first CRP coordination meeting

-Monitor reaction $^{nat}Ni(p, x)$ ^{57}Ni : comparison of 75 experimental datapoints obtained at the VUB between 14.3 and 43.5 MeV with 19 published curves was performed. Overall a good agreement is obtained, the reaction is hence advisable for monitoring up to 44MeV proton energy. The selected data set was sent for evaluation.
The influence of neutron induced ^{57}Ni was studied with 26,7 MeV and 42,9 MeV proton beams : the effect is generally lower than 0,1 % at energies about 2MeV above threshold. The effect due to neutrons generated in Al structural materials (collimators or target holders is more important than from neutrons coming from the target foils.
The results were obtained in collaboration with Atomki-Debrecen and are published.

- For the production of γ-emitters the data on the reactions ^{203}Tl (p, 3n) ^{201}Pb --> ^{201}Tl and ^{nat}Tl (p, xn) ^{201}Pb --> ^{201}Tl were collected.
A comparison of the published experimental results of 8 groups was performed (Blue et al. (78); Lebowitz et al. (75); Bonardi et al. (83); Girardi et al. (75); Lagunas-Solar et al.(79); Lagunas -Solar et al. (78); Qaim et al. (79); Sakai et al (82)EXFOR; Hermanne et al (95)). Some very dicrepant results were found which could not be ascribed to problems with γ abundance.
Only 1 reference was found for results on enriched material for the (p,3n) and for the (p,5n) reaction (in a separate publication by the same authors) from treshold to 35 MeV or 60MeV. Different numerical values are published in the 2 articles and the authors claim the results of the second publication are more trustworthy (Lagunas-Solar et al.)
A selection was made of the concording results and suggestions for a fitting procedure was made when the data set was sumitted to the evaluators
An additional data set for all contaminating *Tl producing reactions up to 40MeV was included.

-Additional experimental data were obtained for the ^{nat}Ti (d, xn) ^{48}V reaction and also for reactions leading to the radionuclides $^{44,46,47,48}Sc$.
Several stacks of ^{nat}Ti were irradiated in Debrecen (up to 10 MeV) and Brussels (up to 21 MeV). The results of the γ-spectrometry were analysed by the Debrecen group and compared with experimental results of different groups. The conclusion is that the proposed reaction is suitable for monitoring. Results were published.

- 2 irradiations of enriched $^{68}Zn(50\mu)/Cu(50\mu)$ stacks with 41 MeV and 32 MeV protons for assessment of ^{68}Zn (p, 2n) ^{67}Ga cross sections were performed. Some problems with interpretation of the results still exist.

2. Additional experimental results and analyses not immediately forseen by the first coordination meeting of the CRP.

- an investigation of secondary electrons influence on beam current measurements was made : a supression voltage of 70V is sufficient ; nearly no influence could be detected in our set-up on proton beams, up to 30% deviations in real beam current was proven for α beams , less than 15% deviations was assessed for deuterons.

-The reactions Ni + d -->$^{61,64}Cu$; $^{56,57}Ni$; $^{56,57,58}Co$; $^{52,54}Mn$ were studied up to 21.5 MeV by stacked foil irradiation at the VUB cyclotron, γ-spectrometry in Brussels and analyses of results in Debrecen. The results were published. The influence of n-induced reactions on cross section determination was studied and published.

-The cross sections of enriched $^{122}Te/Ti$ + d --> ^{123}I up to 21 MeV were determined by stacked foil irradiations (analysed in Debrecen, published).

- By stacked foil irradiations with deuteron beams up to 21.5MeV following reactions were assessed :
Cu + d --> ^{65}Zn (analysed in Debrecen ; published)
Fe + d --> ^{56}Co,^{57}Co (analysed in Debrecen ; published)
Sometimes problems arise with application of the monitor reaction for beam current determination ($^{27}Al(d,x)^{24}Na$) compared to Faraday cup integration. More data needed are needed for this reactions to create a recommended database suitable for monitoring.

-The Mo + d reaction was studied by stacked foil irradiations up to 21 MeV; A complete analysis for all longer lived nuclides was performed resulting in separate production excitation functions for followinf nuclides : ^{99}Mo, ^{92m}Nb, ^{95}Nb, ^{93}Tc, ^{94}Tc, ^{94m}Tc, ^{95m}Tc, ^{96}Tc, ^{99m}Tc.
Part of the results are published.

- Stacked foil iradiations for W+p were performed up to 42MeV. Spectrometric measurement is ready but no analyses was yet performed.

- A test run on Ni/B/Si + p activation was unsuccesful because of melt-down of the target material even at low beam current.

List of publications with VUB co-authorship relative to CRP work1996-1997

S. TAKACS, F. TARKANYI, M. SONCK, A. HERMANNE and S. SUDAR.
Excitation functions of deuteron induced nuclear reactions on ^{nat}Fe and ^{nat}Cu for monitoring deuteron beams.
Proceedings of 14th Int. Conf. on the Applications of Accelerators in Research & Industry, American Institute of Physics, Conference Series, 1997, to be published

S. TAKACS, M. SONCK, A. AZZAM, A. HERMANNE and F. TARKANYI.
Activation Cross Section Measurement of Deuteron Induced Reactions on ^{nat}Ni with Special Reference to Monitoring Beam Performance and Production of ^{61}Cu Medical Isotope.
Applied Radiation and Isotopes, 1997, in press

S. TAKACS, M. SONCK, B. SCHOLTEN, A. HERMANNE and F. TARKANYI.
Excitation Functions of Deuteron Induced Nuclear Reactions on ^{nat}Ti for Monitoring Deuteron Beams.
Radiochimica Acta, 1997, in press

A. HERMANNE, M.SONCK, S.TAKACS and F.SZELECSENYI
Influence of Secondary Neutrons on Cross Section Determination of Proton and Deuteron Induced Reactions on ^{nat}Ni targets.
Proceedings Int. Conf. on Nuclear Data for Sciences and Technology, Trieste, may 1997, to be published.

M. SONCK, S. TAKACS, F. SZELECSENYI, A. HERMANNE and F. TARKANYI
Excitation Functions of Deuteron Induced Nuclear Reactions on ^{nat}Mo from threshold to 21 MeV : an Alternative Route for the Production of $^{94m,99m}Tc$ and ^{99}Mo
Proceedings Int. Conf. on Nuclear Data for Sciences and Technology, Trieste, may 1997, to be published.

M. SONCK, A. HERMANNE, S. TAKACS, F. SZELECSENYI and F. TARKANYI.
Study of the $^{nat}Ni(p,x)^{57}Ni$ Process up to 44MeV for Monitor Purposes.
submitted to **Applied Radiation and Isotopes, 1997.**

S. TAKACS, A.AZZAM, M.SONCK, F.SZELECSENYI, Z. KOVACS, A. HERMANNE and F. TARKANYI.
Excitation function of the $^{122}Te(d,n)^{123}I$ Nuclear Reaction : Production of ^{123}I at low energy cyclotrons.
submitted to **Radiochimica Acta, 1997**

Progress Report from NAC, Faure

IAEA Research agreement No. 8601/CF on "Determination of Exitation Functions for Medical Radioisotopes"

F.M. Nortier, National Accelerator Centre,

P.O. Box 72, Faure 7131, South Africa

Progress Report

This report summarizes the progress in the work done at the NAC since the first CRP meeting in November 1995.

Compilation of published experimental data

According to the Work Plan agreed upon at the first CRP Meeting, the NAC was responsible for the compilation of experimental cross-section data for the two monitor reactions, $^{27}Al(p,X)^{22}Na$ and $^{nat}Cu(p,X)^{56}Co$, and for the $^{127}I(p,5n)^{123}Xe$ reaction employed in the production of ^{123}I at intermediate energies.

Two approaches were followed :

- In the one approach a search was made of the International Nuclear Information System (INIS) database available at the NAC on CD-Rom, covering data published from 1976 up until about February / March 1996. This was followed by a hand search of all the recent issues of popular journals available at NAC (ARI, Radiochimica Acta, NIM, Phys. Rev. C, etc.).

- In the other approach two databases, namely Cross Section Information and Retrieval System (CSIRS) and Nuclear Structure Reference file (NSR) available on the NNDC On-line Service were searched, the former for *particle + product* and *particle + reaction type* and the latter for *nuclear reaction.*

When locally available or from British Library, copies of the relevant hits were obtained and references theirin were scanned for more hits. By combining the results a total of 39 (in the case of $^{27}Al(p,X)^{22}Na$) and 18 (in the case of $^{nat}Cu(p,X)^{56}Co$) hits, representing respectively 435 and 94 data points, were compiled for the two monitor reactions and ten hits were recorded for the $^{127}I(p,5n)^{123}Xe$ reaction. In all three cases the majority of the data points are for proton energies below 100 MeV and, therefore, fall within the scope of the present CRP.

Measurement of excitation functions (outside CRP)

The routine production programme at the NAC is based on a 66 MeV proton beam and special attention is given to the determination of excitation functions for the production of radioisotopes in the intermediate energy region. In the last 18-month period a total of 17 more measured excitation functions for Pr+p up to 100 MeV were added to the existing list of over 160, measured at the NAC up to either 100 or 200 MeV, for proton bombardment of natural Al, Mn, Ni, Cu, Zn, Ge, Kr, Cd, In and Xe. Good progress has also been made with measurements for ^{nat}Ag+p up to 100 MeV.

„Contributions to the Standardisation of Nuclear Data for Medical Radioisotope Production“,

by S. M. Qaim and B. Scholten, Institut für Nuklearchemie, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

Progress Report

The progress achieved in the work since the first CRP meeting in November 1995 is summarized below:

a) Information collection and dissemination

During the last meeting, we had accepted the responsibility to collect detailed available information on the following important monitor and radioisotope production reactions:

$^{nat}Cu(p,x)^{62}Zn$
$^{nat}Cu(p,x)^{63}Zn$
$^{nat}Cu(p,x)^{65}Zn$
$^{124}Te(p,2n)^{123}I$

A thorough search of the literature data on the first three reactions was done, a few erroneous results were screened out, and the whole information was sent to Dr. Tárkányi at Debrecen for onward transmission to the evaluators. The effort involved was much more than anticipated and therefore it took longer than the target date of 1 June 1996. Nonetheless, the material should have reached the evaluators by October 1996. The responsibility of the fourth reaction was transferred to ATOMKI Debrecen.

b) Experimental measurements

- A detailed study on the monitor reaction $^{nat}Ti(d,xn)^{48}V$ was completed from threshold up to 22 MeV. It was a joint effort between ATOMKI Debrecen, VU Brussels and FZ Jülich. A technical paper based on the experimental results has been accepted for publication in Appl. Radiat. Isotopes.
- Measurements on the excitation function of the $^{18}O(p,n)^{18}F$ reaction were started using 95% enriched $^{18}O_2$. The standard gas-cell technique was employed. Several irradiations were done both at Jülich and Debrecen and the data analysis is in progress. It was realized that measurements up to 30 MeV may be interesting. The collaboration has therefore been extended and measurements are planned at Brussels also.
- Several other measurements were done in collaboration with ATOMKI Debrecen, e.g. p-, ^3He- and α-particle induced reactions on ^{nat}Ne to produce ^{22}Na and ^{24}Na, d-induced reactions on ^{123}Te to produce ^{124}I, etc.
- In cooperation with the IAEA, measurements were performed on the $^{100}Mo(p,pn)^{99}Mo$ and $^{100}Mo(p,2n)^{99m}Tc$ reactions from threshold to 65 MeV. Data analysis is in progress. The results should provide information on the production of ^{99m}Tc at a cyclotron.

The latter two studies were outside the CRP. Nonetheless, the CRP served as a forum for further discussions.

c) Future plans

- Collection and dissemination of information on the most commonly used reactions for the production of positron emitters ^{11}C, ^{13}N, ^{15}O and ^{18}F.
- Completion of measurements on the $^{18}O(p,n)^{18}F$ process.
- Integral tests on a few selected evaluated reactions.
- Formulating guidelines (together with Dr. Tárkányi) on the measurement and use of evaluated nuclear data.
- Initiation of efforts relevant to the identification of discrepancies in important nuclear data.

DEVELOPMENT OF CHARGED PARTICLE CROSS SECTION CALCULATION METHODS FOR MEDICAL RADIOISOTOPE PRODUCTION

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Submitted to Second Research Co-ordination Meeting on
"Development of Reference Charged Particle Cross Section Data Base for Medical Radioisotope Production"

SUMMARY

The activity on the development of charged particle cross section calculation methods for medical radioisotope production was carried out in several directions:

- Compilation of the production cross sections for commonly used medical radioisotopes, in particular I-123, In-111 and Tl-201.

- Development of calculation methods and the study of level density effects on calculated excitation functions for production of Cs, Xe, I, Tl, Pb and Bi.

- Evaluation of experimental and calculation results for the reactions specified at the first CRP Meeting.

-Creation of data files for production cross sections of I-123, Tl-201 and In-111.

- Estimations of the reaction cross sections for the production of other advantageous radioisotopes.

According to the first year programme the following work was performed:
-The calculation, analysis and comparison with experimental data for the reaction cross sections for the production of commonly used medical radioisotopes I-123 and Tl-201 have been performed. The production of I-123 and Tl-201 was considered either directly through nuclear reactions on Te and Hg targets or indirectly through nuclear reactions on I, Xe, Tl, Pb and Bi via the decay of its radioactive precursors Xe-123, Cs-123, Pb-201 and Bi-201. The competing reactions which influence the radioisotope purity were calculated and analyzed also. More than 50 reactions induced by protons,

deuterons and alpha-particles and used for radioisotope production in the regions Z=51-55 and Z=80-83 were calculated using two versions of the ALICE code. The comparison with the compiled experimental data and statistical analysis was performed. It is shown that the new version -ALICE-IPPE- gives a better description of experimental data in a wide energy region, especially for proton induced reactions. The paper "Excitation function calculation method analysis for radioisotope production of Iodine and Thallium" is now in press (Appl. Radiat. Isot.). The version of the ALICE-IPPE code was installed in INC KFA, Juelich, and in Hannover (Institute of Radioprotection and Radioecology).

- The calculation methods were developed and level density effects on the calculated excitation functions for the production of Cs, Xe, I, Tl, Pb and Bi were studied. The available experimental data were compared with excitation functions calculated in the energy range up to 100 MeV using two versions of the ALICE code. It was shown that generalized superfluid model for the level density ensures better description of available experimental data. (Preprint IPPE, Obninsk, 1996).

- The analysis and evaluation of the excitation functions for the following reactions was performed using the calculation results and compiled experimental data:
^{127}I(p,5n)^{123}Xe, ^{111}Cd(p,n)^{111}In, ^{112}Cd(p,2n)^{111}I, ^{nat}Cd(p,x)^{111}In, ^{123}Te(p,n)^{123}I, ^{124}Te(p,n)^{124}I, ^{203}Tl(p,3n)^{201}Pb, ^{205}Tl(p, 5n)^{201}Pb, ^{63}Cu(p,2n)^{62}Zn, ^{65}Cu(p,3n)^{63}Zn, ^{65}Cu(p, n)^{65}Zn, ^{65}Cu(p,4n)^{62}Zn.
The numerical data for production of I-123, Tl-201 and its precursors are available for these reactions. The cross section calculations analysis for the reactions on Ni, Ti and Al were performed also.

Method of thallium-199 production via the reaction ^{200}Hg (p, 2n) ^{199}Tl induced with protons in the energy range 10-35 MeV was investigated. The excitation functions for the ^{200}Hg (p, 2n) ^{199}Tl reaction and accompanying ^{200}Hg (p, n) ^{200}Tl and ^{200}Hg (p, 3n) ^{198}Tl reactions were performed with ALICE-IPPE code. Thick target yields for thallium-199, thallium-200 and thallium-198 and radionuclidic purity thallium-199 were calculated using excitation functions obtained.

Development of Reference Charged Particle Cross Section Data Base for Medical Radioisotope Production

Progress Report

Institute of Nuclear Research of the Hungarian Academy of Sciences
Debrecen, Hungary

(F. Tárkányi, S. Takács, F. Szelecsényi)

After the First Research Coordination Meeting in Vienna, Austria, 15-17 November 1995 the activity of the Debrecen (ATOMKI) group in the CRP can be summarized as follows:

Compilation work

Monitors

According to the workplan, the ATOMKI compiled the available experimental cross section data of the $^{nat}Ti(p,x)^{48}V$ monitor reaction.

The ATOMKI was also participated in the compilation work of experimental data of $^{nat}Ni(p,x)^{57}Ni$ in collaboration with VUB Brussel, Belgium.

Gamma-emitters

The ATOMKI group compiled the experimental data of the following reactions:
$^{111}Cd(p,n)^{111}In$
$^{112}Cd(p,x)^{111}In$
$^{111}Cd(p,n)^{111}In$.

In the collaboration with the KFA Jülich, Germany the below listed reactions were also compiled:

$^{124}Te(p,2n)^{123}I$
$^{123}Te(p,n)^{123}I$

Experimental Measurements

Reaction $^{nat}Ti(d,x)^{48}V$ (experimental data)

The ATOMKI, Debrecen in collaboration with the VUB Brussels, Belgium and KFA Jülich, Germany completed the experimental measurements of the $^{nat}Ti(d,x)^{48}V$ reactions and other deuteron induced reactions on ^{nat}Ti. A work based on the obtained data were accepted for publication in Applied Radiation and Isotopes (see List of Supplement Document).
Method: :Stacked foil method, activation technique

Reaction $^{68}Zn(p,2n)^{67}Ga$ (discrepant data)

Excitation function of $^{68}Zn(p,2n)^{67}Ga$ reaction was measured up to 44 MeV on enriched ^{68}Zn in collaboration with VUB Brussels, Belgium. 21 foils was irradiated with 42 MeV primary proton energy. The experimental cross section data are in good agreement with our previous data. One additional irradiation is however required to have overlapping energy region between the two earlier irradiations. According to our plan the additional experiment and the complete data evaluation will be finished at the end of 1997.
Method: Enriched ^{68}Zn, stacked foil method, activation technique.

Reaction $^{18}O(p,n)^{18}F$ (discrepant data)

Excitation function of $^{18}O(p,n)^{18}F$ reaction was measured at moderate energy resolution in collaboration with KFA Jülich, Germany up to 20 MeV proton energy. Moderate resolution have been achieved by using thick targets in irradiations at CV28 accelerator in Jülich and by continuos shifts of the bombarding energy in experiments at MGC 20E cyclotron in Debrecen.
The evaluation of the experimental data is in progress and additional irradiations are planned at higher energies.

General

Coordination of collection of experimental data

Most of the experimental data were supplied to Debrecen before 1 June 1996. Some compiled data were also supplied in December 1996.

There were problems in the file transfer to evaluating groups, especially in EXCEL format.(The files was sent through e-mail and via floppy discs.)

The data were compiled exclusively in EXCEL format. The file contains numerical data, description of experimental circumstances, figures, comments.

The submitted files were individual both in shape and content.

More detailed analysis of original data is required for all experimental groups.

Task recommendations

Preparation for guidelines for proper and accurate measurement and proper use of data have been started and will be published in a CRP TECDOC and in Radiochimica Acta.

The EXFOR compilation of the data used in the CRP program are in progress.

New recommendations

More critical comparison for the experimental groups.

Compilation format EXCEL (only)

Importance of the compilation of side reactions for evaluators.

XA9745770

CNDC Charged Particle Group Progress Report

Zhuang Youxiang
(China Nuclear Data Center, CIAE)

1. The Evaluations and Calculations of Charged Particle Reaction Data for Medical Radioisotope Production (IAEA Research Contract No. 8600 / RB, 1995–1996)

The related experimental data were collected up to 1995. The excitation functions of ^{11}B, ^{13}C, ^{77}Se, $^{186}W(p,n)$ and $^{16}O(p,\alpha)$ reactions were measured with the aid of either residual nucleus activity or outgoing neutron or α–particle methods. Enriched samples, stacked target irradiation or energy degradation by foils, beam current integration, chemical separation, separate monitor–foil, coincidence technique, NaI(Tl) crystal, plastic scintillator, Ge–Li detector, BF3 neutron counter etc. were used in these measurements.

In general, there are some experimental data in energy range from threshold to 30 MeV, thus it is necessary for each reaction to do theoretical calculation for interpolation or / and extrapolation of experimental data up to 80 MeV.

2. The Systematics Research on (p,n) and (p,2n) Reactions Excitation Functions

The existing charged particle nuclear data can't meet applied requirements. It is necessary for this purpose to do systematics research. There are two ways: one is from simplified theory fomula, and another from empirical method.

On the basis of Planck formula of black body radiation and experimental excitation functions of (p,n) and (p,2n) reactions, the empirical systematic formula is presented, which includes two adjustable parameters, incident proton energies from threshold to 150 MeV, target masses from 30 to 243, and reproduces excitation functions of (p,n) and (p,2n) reactions well.

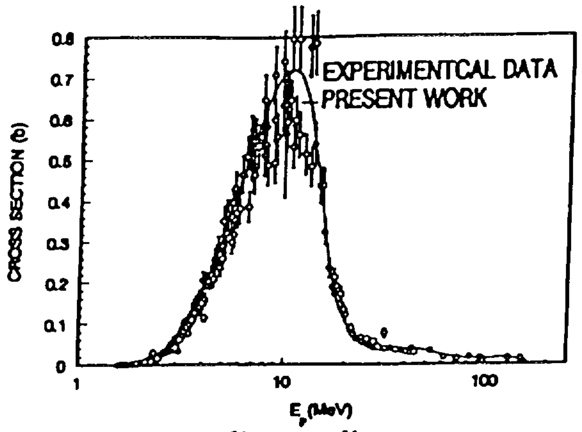

Fig.1 $^{51}V(p,n)^{51}Cr$ reaction

3. Progress on CRP Contract No. 8600 / R1 / RB, 1996–1997

3.1 Evaluation of Monitor Excitation Functions

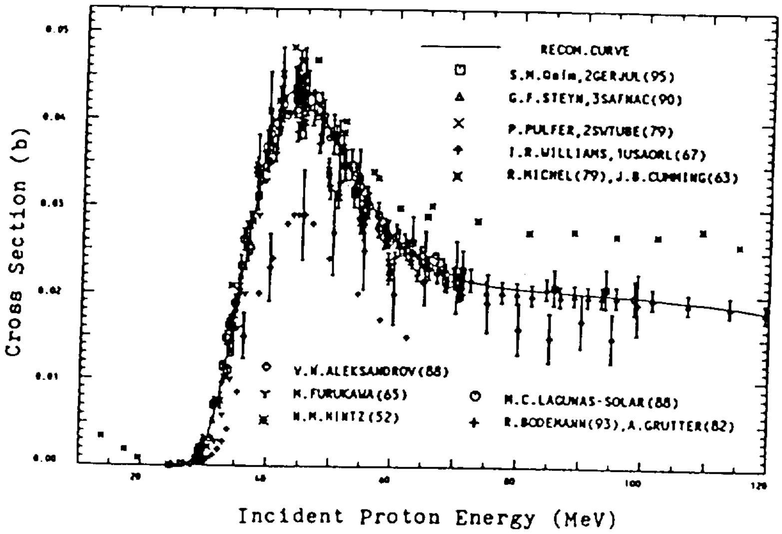

Fig. 2 $^{nat}Al(p,x)^{22}Na$ reaction

3.2 Evaluation of Excitation Functions for g–emitters

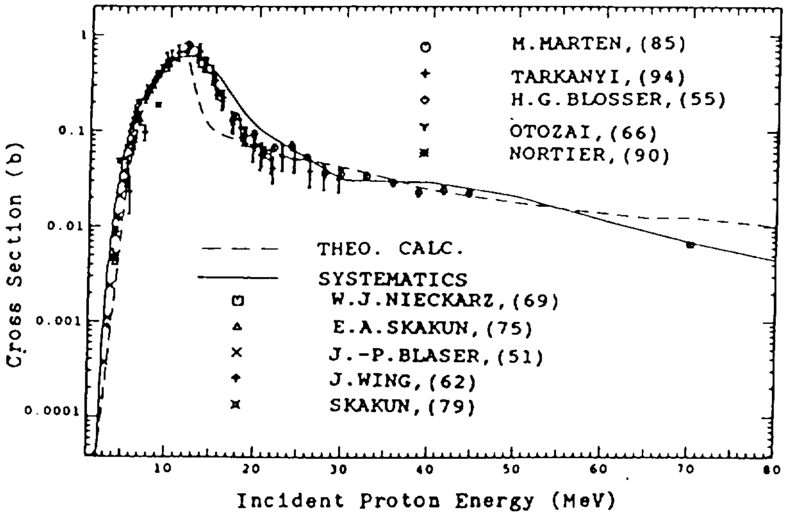

Fig. 3 $^{111}Cd(p,n)^{111}In$ reaction

THE SYSTEMATICS RESEARCH ON (p, n) AND (p,2n) REACTIONS EXCITATION FUNCTION

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1 Introduction

On the basis of Planck formula of black body radiation and experimental excitation functions of (p,n) and(p,2n) reactions, an empirical systematics formula is presented, which includes two adjustable parameters , incident proton energies from threshold to 150 MeV, target masses from 44 to 243, and reproduces excitation functions of (p,n) and (p,2n) reactions well.

2 Establishment of systematics empirical formula

The Planck radiation formula of black body is as follows:

$$M(\nu) = \frac{C_0 \nu^3}{e^{C_1 \nu / T} - 1} \tag{1}$$

we have : $M(\nu) \Leftrightarrow \sigma(E)$, $\nu \Leftrightarrow E$, $C_1/T \Leftrightarrow \beta_0$
thus a preliminary formula of reaction cross section is obtained:

$$\sigma(E) = \frac{C_0 E^3}{e^{\beta_0 E} - 1} \tag{2}$$

Because there exits a threshold E_{th} for a certain reaction ,$\sigma(E)=0$,when E $\le E_{th}$; we replace E with (E $-E_{th}$) in formula (2)

$$\sigma(E) = \frac{C_0 (E - E_{th})^3}{e^{\beta_0 (E - E_{th})} - 1} \tag{3}$$

It can describe the curves of (p,xn) reaction excitation functions roughly, at E<30MeV.

In order to raise the values of curves at E>30MeV, we put some β functions into formula (3).

For (p,n) reaction, we have:

$$\sigma_{p,n} = \frac{C_0 (E - E_{th})^3}{e^{\beta_0 (E - E_{th})-1}} \prod_{i=1}^{6} \beta_i \tag{4}$$

where, $$\beta_1 = \frac{1}{1 + \left(\frac{C_2}{E - E_{th}}\right)^2}$$

For (p,2n) reaction we have:

$$\sigma_{p,2n}(E) = \sigma_1(E) + \sigma_2(E) \delta_{E,C_3} \tag{5}$$

where, $\delta_{E,C_5} = \begin{cases} 0 \quad , & E = C_5 \\ 1 \quad , & E \neq C_5 \end{cases}$, $\sigma_1(E) = \dfrac{C_0(E-E_{th})^3}{e^{\beta_0(E-E_{th})}-1}\beta_1\beta_2\beta_3$,

$\sigma_2(E) = \sigma_1(C_5)(C_5/E)^{C_6}\beta_4, \beta_2 = e^{(E/C_1)^{C_2}}$

where c_0, c_2 and C_0, c_3 are adjustable parameters(also the so- called local parameters). Are there systematics behavior of parameters c_0, c_2 and c_0, c_3 ? The answer is certainly yes. Using the minimum deviation, the systematic formulas of parameters c_0, c_2 and c_0, c_3 are as follows:

for (p,n) reaction we have:

$$C_0 = (-0.009556 + 0.1665\frac{N-Z}{A})(1-0.3e^{-1800(\frac{N-Z}{A}-0.185)^2}) \tag{7}$$

$$C_2 = \frac{0.000412A^{2.1484} - (A/100)^{2.9888} + (A/150)^{6.7} + (A/200)^{24}}{1+0.4e^{10(67-A)}} \tag{8}$$

For (p,2n) reaction ,we have:

$$C_0 = \begin{cases} 0.002635e^{(20.485X+(\frac{0.06514}{X})^{20}-(\frac{0.08}{X})^{5})} & X < 0.19796 \\ 2.476935 - 11.7X & X \geq 0.019796 \end{cases} \tag{9}$$

$$C_3 = \begin{cases} 0.6057e^{(3.5|X-0.1323|+132|X-0.1323|^{1.57})} & X < 0.2055 \\ (260.7769 - 1253.8X) & \\ (1 - \dfrac{5.65X}{1+0.0000001e^{1000000(0.20775-X)}}) & X \geq 0.2055 \end{cases} \tag{10}$$

where $X = \frac{N-Z}{A}$.

The values of c_0, c_2 and c_0, c_3 extracted from the above systematics are called regional parameters .

Using the regional parameters c_0, c_2 the excitation function of the (p,n) reaction can be predicted . when 50<A<120, the comparison with the existing measured excitation functions shows that the agreements between the predicted and measured curves are very good (see Fig. 2); while for A<51 and A>120 nuclei , agreement between the excitation function predicted by the systematics and the existing measured excitation functions is not satisfactory. For (p,2n) reaction, agreement between the excitation function predicted by the systematics and the existing measured excitation functions is very satisfactory(see Fig. 1).

3 Figures

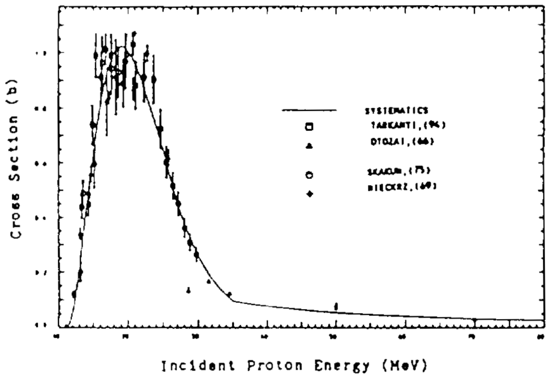

Fig. 1 $^{112}Cd(p,2n)^{111}In$ reaction

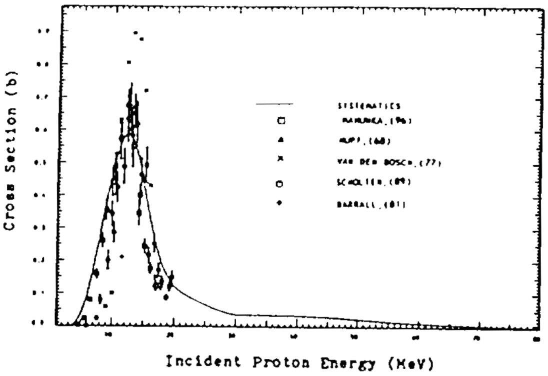

Fig. 2 $^{123}Te(p,n)^{123}I$ reaction

Nuclear Modeling Applied to Radioisotope Production

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and
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Abstract

Calculated excitation functions are provided for all proton induced reactions listed for the Coordinated Research Program (CRP) on Development of a Reference Charged Particle Cross Section Data Base for Medical Radioisotope Production under the International Atomic Energy Agency (IAEA). The excitation functions are compared with experimental data sets as provided to the CRP. We discuss the merit of calculated results with respect to the experimental data.

1) Introduction

In this report we present tabular results of calculated excitation functions for production of isotopes useful as beam monitors or for medical use. This is done as part of an IAEA-CRP. The reactions considered are summarized on p2, followed by the tabular information. We present figures, some with experimental results as presented to the CRP, some with only calculated yields. These are presented following the tables.

The question to be addressed is to what degree nuclear model codes may aid in data evaluation and production. We will first give very brief comments on the comparisons between calculated excitation functions and experimental yields. We will conclude with a few subjective opinions on the question of the role of theory in evaluation. All calculated results to be presented in this work were from the HMS Alice code[1], using the Monte Carlo precompound formulation, with either a Fermi gas level density, or using the shell dependent model of Kataria and Ramamurthy[2]. The optical model was used for inverse reaction cross sections, with an energy mesh size of 0.1 MeV to 0.5 MeV in order to get smooth behavior with change of incident energy.

2) Reference

The full report (see next page) is available upon request from the authors.

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Nuclear Modeling Applied to Radioisotope Production

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