IAEA
International Atomic Energy Agency

INDC(NDS)-0591
Distr. G+NM+SD

INDC International Nuclear Data Committee

Summary Report

Consultants' Meeting on

Improvements in Charged-Particle Monitor Reactions and Nuclear Data for Medical Isotope Production

IAEA Headquarters
Vienna, Austria

21-24 June 2011

Prepared by

R. Capote Noy
IAEA Nuclear Data Section
Vienna, Austria

and

F.M. Nortier
Los Alamos National Laboratory
Los Alamos, NM, USA

September 2011

IAEA Nuclear Data Section, Vienna International Centre, A-1400 Vienna, Austria

Selected INDC documents may be downloaded in electronic form from
http://www-nds.iaea.org/reports-new/indc-reports/
or sent as an e-mail attachment.
Requests for hardcopy or e-mail transmittal should be directed to services@iaeand.iaea.org
or to:
Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
A-1400 Vienna
Austria

Produced by the IAEA in Austria

September 2011

INDC(NDS)-0591
Distr. G+NM+SD

Summary Report

Consultants' Meeting on

Improvements in Charged-Particle Monitor Reactions and Nuclear Data for Medical Isotope Production

IAEA Headquarters
Vienna, Austria

21-24 June 2011

Prepared by

R. Capote Noy
IAEA Nuclear Data Section
Vienna, Austria

and

F.M. Nortier
Los Alamos National Laboratory
Los Alamos, NM, USA

Abstract

A Consultants' Meeting on "Improvements in Charged–Particle Monitor Reactions and Nuclear Data for Medical Isotope Production" was held at IAEA Headquarters, Vienna, Austria to define the scope, deliverables and appropriate work programme of a possible Coordinated Research Project (CRP) on the subject. The main data areas requiring improvements are monitor reactions for charged-particle beams, production of novel positron emitters, and production of alpha emitters. In all these areas special attention was also given to the need for measurements and re-evaluations of decay data. Detailed deliverables of the planned CRP were proposed.

September 2011

TABLE OF CONTENTS

1. Introduction 7

2. Meeting Summary 8

  2.1. Charge to the Consultants 8
  2.2. General outcome 8
  2.3. Scope of the Coordinated Research Project (CRP) 8
    2.3.1. Monitor reactions for charged particle beams 8
    2.3.2. Discrepancies and new directions in data for production of diagnostic gamma emitters 9
    2.3.3. Production of novel positron emitters 9
    2.3.4. Production of therapeutic isotopes 10
    2.3.5. Decay data 10

3. Presentations 11

  3.1. Overview of the IAEA database for medical applications, R. Capote 11
  3.2. Nuclear data relevant to novel positron emitters, S.M. Qaim 11
  3.3. Status of the IAEA medical database and proposal for upgrade, F. Tárkányi 12
  3.4. Activities of the National Metrology Institute (NMI), M.-M. Bé 12
  3.5. High-energy accelerator production of ^{225}Ac: cross sections for ^{232}Th + p, F.M. Nortier 13
  3.6. Status of charged-particle induced reaction cross-section measurements by using the stacked-foil activation method, G. Kim 14
  3.7. Nuclear data for medical RI production by using accelerator neutrons, Y. Nagai 15

ANNEXES

A: Agenda 17

B: List of Participants 19

1. Introduction

Medical applications of nuclear radiation are of considerable interest to the IAEA. Nowadays both diagnostic and therapeutic procedures are widely used clinically and in research studies. The increasing need of radioisotopes for medical applications related to cancer diagnostics and therapy is very well established. Up to half of all cancer patients worldwide receive some type of radiation therapy sometime in the course of their treatment.

Cyclotrons and accelerators, available in recent years in an increasing number of countries, are used for the production of radioisotopes for both diagnostic and therapeutic purposes. Reactors are also widely employed to produce radioisotopes for many different applications. Nuclear data are required both for accelerator and reactor production of radionuclides. Those needs were initially addressed by a Coordinated Research Project (CRP) on "Charged Particle Cross-Section Database for Medical Radioisotope Production: Diagnostic Radioisotopes and Monitor Reactions" that started in 1995 and concluded in 2001 with the publication of a comprehensive report, IAEA-TECDOC-1211[1]. In order to address data needs for the production of therapeutic radionuclides, a new CRP on "Nuclear Data for the Production of Therapeutic Radionuclides" began in 2003 and was completed in 2007. The CRP produced a much needed database and a handbook[2] covering reactions used for medically important therapeutic radionuclides. The database containing data from both CRPs is available on: **http://www-nds.iaea.org/medportal/**. These recommended cross-sections were sufficiently accurate to meet the demands of all current applications at the time. The improved quality of the nuclear data generated during these CRPs made radionuclide production much more efficient and also enhanced nuclide quality through improved purity. However, some discrepancies have arisen along with the need to improve aspects of the monitor reactions – particularly extensions to higher energies that have become a priority.

The newer developments in medical imaging and therapy utilizing novel diagnostic and therapeutic radionuclides called for a further expansion of the database. In this regard the novel positron emitters and alpha-emitting radionuclides require attention. Keeping these requirements in mind, a Consultants' meeting was called.

Six consultants attended the meeting. R. Capote (IAEA, Vienna, Austria) served as Scientific Secretary, S.M. Qaim (Forschungszentrum Jülich, Germany) was elected Chairman of the meeting and F.M. Nortier (LANL, USA) agreed to act as rapporteur. The approved Agenda is attached (Appendix A), as well as a list of participants and their affiliations (Appendix B).

M. Venkatesh (Director, NAPC) welcomed the participants, and emphasized the significance of their role in assessing existing data needs and defining the scope and programme of work for a successful CRP.

---

[1] IAEA-TECDOC-1211, "Charged Particle Cross-Section Database for Medical Radioisotope Production: Diagnostic Radioisotopes and Monitor Reactions", IAEA Technical Report, Vienna, May 2001. Available online: http://www-nds.iaea.org/reports-new/tecdocs/iaea-tecdoc-1211.pdf

[2] E. Běták, A.D. Caldeira, R. Capote, *et al.*, "Nuclear Data for the Production of Therapeutic Radionuclides", IAEA Technical Reports Series No. 473 (S.M. Qaim, F. Tarkanyi, R. Capote (Eds.)), Vienna, Austria, 2011.

2. Meeting Summary

2.1. Charge to the consultants

The charge to the consultants included assessment of the need for a new Coordinated Research Project (CRP) and to define the scope, deliverables and propose possible participants. The focus of a new CRP must be limited to monitor reactions for charged particle beams, production of novel positron emitters, and production of alpha emitters. In all these areas special attention should also be given to decay data.

2.2. General outcome

The consultants determined that solid grounds exist for a new CRP by the IAEA. Experience from the last two CRPs in this field (“Charged Particle Cross-Section Database for Medical Radioisotope Production: Diagnostic Radioisotopes and Monitor Reactions” and “Nuclear Data for the Production of Therapeutic Radionuclides”) showed that there is considerable worldwide interest among the user community in the field of medical applications as well as in other fields such as fusion, analytical applications and the development and testing of nuclear models. The consultants singled out the main areas requiring improvements as: i) monitor reactions for charged-particle beams, ii) removal of data discrepancies in production of diagnostic gamma emitters, iii) production of novel positron emitters and positron emitters via generator isotopes and iv) production of alpha emitters. In all these areas special attention was also to be paid to the need for measurements and re-evaluations of decay data.

The need for providing the user community with uncertainty values in the recommended data was discussed at length. It was concluded that all recommended values are expected to have uncertainties.

In general, measurements of new decay data, cross-section data and accurate integral yields for validation purposes were recommended.

The consultants made the observation that the US National Nuclear Data Center (NNDC) web site (www.nndc.bnl.gov/) does not provide a link to the widely-used IAEA-recommended charged-particle beam monitor cross sections (www-nds.iaea.org/medical/monitor_reactions.html) and medical portal web pages (www-nds.iaea.org/medportal). A request to provide such links should be directed to NNDC.

2.3. Scope of the Coordinated Research Project (CRP)

The consultants recommend a CRP with the following scope:

1. Updating of existing beam monitor data, including uncertainties and extension of energy range where appropriate. Inclusion of additional monitor reactions.
2. Inclusion of data for emerging diagnostic and therapeutic radionuclides as identified below.
3. Identification and correction of deficiencies in existing recommended data.
4. Re-evaluation of decay data as identified.
5. Measurement of new decay and cross-section data as identified.

Details are given below.

2.3.1. Monitor reactions for charged particle beams

1. Resolve the inconsistencies in ^{nat}Cu(p,x)^{62,63,65}Zn cross sections with regard to isotope activity ratios. Possibly re-evaluate the reactions so that the isotope activity ratios are conducive to energy determination for low energy machines.
2. Include the ^{nat}Cu(p,x)^{58}Co for higher energies (>50 MeV) and ^{nat}Mo(p,x)$^{96m+g}$Tc reactions.

3. Update ^{27}Al(p,x)^{22,24}Na including isotope activity ratios (up to 800 MeV), ^{27}Al(d,x)^{22,24}Na including isotope activity ratios, ^{27}Al(^{3}He,x)^{22,24}Na for higher energies up to 100 MeV and ^{27}Al(α,x)^{22,24}Na.
4. Include ^{nat}Cu(d,x)^{62,63,65}Zn and ^{nat}Ni(d,x)^{56,58}Co reactions.
5. Include ^{nat}Ti(d,x)^{46}Sc reaction for higher energy deuterons.
6. Re-evaluate ^{62,63}Zn decay schemes, with special emphasis on gamma intensities. Also re-evaluate ^{61}Cu decay scheme with its relatively weak gammas.
7. Indicate uncertainties in recommended data.

2.3.2. Discrepancies and new directions in data for production of diagnostic gamma emitters

1. In connection with ^{123}I production from ^{124}Xe targets, re-evaluate ^{124}Xe(p,2n)^{123}Cs and ^{124}Xe(p,pn)^{123}Xe reactions and include ^{124}Xe(p,x)^{121}I side reaction.
2. Include available data for gamma emitters produced by neutrons into the Medical Dissemination System:
   ^{98}Mo(n,γ) ^{99}Mo(^{99m}Tc),^{235}U(n,f)^{99}Mo(^{99m}Tc)… *this could be addressed outside the proposed CRP by external consultants.*
3. Include ^{100}Mo(p,2n)^{99m,g}Tc, ^{100}Mo(p,pn)^{99}Mo, ^{100}Mo(d,3n)^{99m,g}Tc and ^{100}Mo(d,p2n)^{99}Mo for evaluation.
4. Evaluate ^{100}Mo(n,2n)^{99}Mo and ^{90}Zr(n,p)^{90m,g}Y cross sections. Consider new measurements with d/C breakup neutrons both for validation of data and for production. Also consider photonuclear reactions for production of ^{99}Mo.
5. Re-evaluate the ^{112}Cd(p,2n)^{111}In reaction, including new data. New measurements may be necessary.

2.3.3. Production of novel positron emitters

A. Direct production

1. Include ^{58}Ni(p,α)^{55}Co, ^{54}Fe(d,n) ^{55}Co and ^{56}Fe(p,2n)^{55}Co production data.
2. Include ^{61}Ni(p,n)^{61}Cu and ^{64}Zn(p,α)^{61}Cu production data.
3. A new evaluation of ^{64}Cu decay data has been done by the Decay Data Evaluation Project, DDEP[3]. A paper describing the measurements will be published. A possible remaining discrepancy in the weak gamma line intensity of ^{64}Cu was discussed.
4. Include ^{66}Zn(p,n) ^{66}Ga and ^{63}Cu(α,n) ^{66}Ga production data since they are gaining importance in theragnostics (defined as "deemed suitable for therapy and diagnostics" – "theragnostics"). Re-measure and re-evaluate the positron intensity of ^{66}Ga via beta-gamma counting and X-ray intensities.
5. Include ^{68}Zn(p,n) ^{68}Ga and ^{65}Cu(α,n) ^{68}Ga direct production data.
6. Include ^{nat}Ge(p,xn)^{72}As production data. Re-measure and possibly re-evaluate positron intensity of ^{72}As via beta-gamma counting and X-ray intensities.
7. Include ^{76}Se(p,n)^{76}Br, ^{77}Se(p,2n)^{76}Br and ^{75}As(α,3n)^{76}Br production data. Re-evaluate positron intensity of ^{76}Br.
8. Update the ^{86}Sr(p,n)^{86}Y production data and include ^{85}Rb(α,3n)^{86}Y and ^{88}Sr(p,3n)^{86}Y. There is some uncertainty in the positron intensity. Re-measure and possibly re-evaluate positron intensity of ^{86}Y via beta-gamma counting and X-ray intensities.
9. Include ^{89}Y(p,n)^{89}Zr and ^{89}Y(d,2n)^{89}Zr production data. Possibly re-evaluate positron intensity of ^{89}Zr.

---

[3] Available online at http://www.nucleide.org/DDEP_WG/DDEPdata.htm (^{64}Cu data)

10. Include ^{94}Mo(p,n)^{94m}Tc and ^{92}Mo(α ,x)^{94m}Tc production data. Re-evaluate positron intensity of ^{94m}Tc.
11. Include ^{55}Mn(p,4n)^{52}Fe, ^{nat}Ni(p,x)^{52}Fe and ^{52}Cr(^{3}He,3n)^{52}Fe production data.
12. Include ^{75}As(p,3n)^{73}Se and ^{70}Ge(α,n)^{73}Se production data. Re-measure and possibly re-evaluate positron intensity of ^{73}Se.
13. Include ^{111}Cd(p,2n)^{110m}In ($T_{1/2}$ = 69 min) production data.
14. Include ^{120}Te(p,n)^{120}I and ^{122}Te(p,3n)^{120}I production data. Possibly re-evaluate the positron intensities of ^{120}I.

B. Production via generator isotopes

1. ^{82}Sr/^{82}Rb: re-evaluate ^{nat}Rb(p,xn)^{82}Sr production data to include recent measurements.
2. ^{68}Ge/^{68}Ga: recommend new measurements for ^{nat}Ga(p,xn)^{68}Ge, ^{69}Ga(p,2n)^{68}Ge and ^{71}Ga(p,4n)^{68}Ge production reactions and re-evaluate.
3. ^{62}Zn/^{62}Cu: include ^{63}Cu(p,2n)^{62}Zn production data.
4. ^{72}Se/^{72}As: include ^{75}As(p,4n)^{72}Se and ^{nat}Br(p,x)^{72}Se production data.

2.3.4. Production of therapeutic isotopes

A. Alpha emitters

1. ^{229}Th→^{225}Ra→^{225}Ac→^{213}Bi:
    a. Include ^{232}Th (p,x)^{225}Ra production data, and include new measurements up to 200 MeV.
    b. Include ^{232}Th (p,x)^{225}Ac production data and add new measurements up to 200 MeV.
    c. Recommended data for ^{226}Ra(p,2n)^{225}Ac exist. Additional measurements would be good, but execution is difficult.
    d. ^{227}Ac long-lived (21.8y) impurity: Include ^{232}Th (p,x)^{227}Ac production data and add new measurements up to 200 MeV.
2. ^{230}U→^{226}Th: ^{231}Pa(d,3n) , ^{231}Pa(p,2n), ^{232}Th (p,3n). Measurements are foreseen.
3. ^{227}Th→^{223}Ra: ^{232}Th(p,x)^{227}Th evaluate. New measurements are in progress.

B. Electron and X-ray emitters

1. Include ^{130}Ba(n,γ)^{131}Ba, ^{131}Xe(p,n)^{131}Cs and ^{133}Cs(p,3n)^{131}Ba data for production of ^{131}Cs.
2. ^{103}Pd: decay scheme should be re-evaluated.

2.3.5. Decay data

Isotope	Comments	Priority
^{66}Ga	Large uncertainties in positron intensities, re-measure and re-evaluate	1
^{86}Y	Large uncertainties in positron intensities, re-measure and possibly re-evaluate	1
^{103}Pd	Re-evaluate	1
^{73}Se	Re-measure and possibly re-evaluate	2
^{94m}Tc	Re-evaluate	2
^{72}As	Re-measure and possibly re-evaluate	2
^{62}Zn	Re-evaluate with special emphasis on gamma intensities	2

^{52}Fe	Re-evaluate	3
^{76}Br	Re-evaluate	3
^{89}Zr	Re-evaluate	3
^{120}I	Re-evaluate	3
^{230}U	Re-evaluate	3

3. Presentations

3.1. Overview of the IAEA database for medical applications, R. Capote

R. Capote (IAEA) gave an overview of the status of IAEA nuclear databases for medical applications with special emphasis on beam monitors for charged-particle induced reactions and cross sections for the production of radioisotopes. Over the previous thirty years, many laboratories have reported significant bodies of experimental data relevant to medical radionuclide production, and charged-particle data centres have compiled most of these data. A systematic effort was devoted to their standardization and assembly within two IAEA Coordinated Research Projects that were active from 1995 until 2007. Radionuclides for both diagnostic and therapeutic purposes were covered. Compiled data included neutron and charged-particle induced reactions to be used in reactor and accelerator isotope production programmes.

Accurate and complete knowledge of nuclear data is essential for the production of radionuclides for radiotherapy in order to achieve the specific activity and purity required for efficient and safe clinical application. The developed databases are widely used and referenced in many publications. They have also been used as basic data for additional IAEA projects devoted to the establishment of efficient and cost-effective methods for the production of radionuclides.

3.2. Nuclear data relevant to novel positron emitters, S.M. Qaim

S.M. Qaim (FZ Jülich, Germany) gave an overview of novel positron emitters under development. He emphasized that in molecular imaging, the importance of longer-lived positron emitters, also termed as non-standard or innovative PET radionuclides, has been constantly on the rise, especially because they allow studies on slow metabolic processes and in some cases furnish the possibility of quantification of radiation dose in internal radiotherapy. Considerable efforts have been made worldwide and about 25 positron emitters have been developed. Those efforts relate to interdisciplinary studies dealing with basic nuclear data, development of high current targetry for charged-particle irradiation, efficient radiochemical separation and quality control of the desired radionuclide, and recovery of the enriched target material for re-use. The review was limited to a discussion of nuclear data.

As regards decay data, the distinctive features (in comparison to commonly used positron emitters) are: (a) relatively long half-lives, (b) rather high positron end-point energies, (c) generally low positron intensities, and (d) associated γ-rays. These features affect the resolution of scans and call upon the development of some special algorithms in the analysis of images. In general, the decay data are known but occasionally there is some uncertainty in positron emission intensities, mainly arising from (i) use of impure samples, and (ii) lack of high-precision β-ray spectroscopy. Attention was drawn to the IAEA technical report INDC(NDS)-0535[4] on this topic.

---

[4] Summary Report Consultants' Meeting on High-precision beta-intensity measurements and evaluations for specific PET radioisotopes, R. Capote Noy and A. Nichols, INDC(NDS)-0535, IAEA, Vienna, Austria, 2008, available online at http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0535.pdf

As regards production data, for each radionuclide several nuclear routes were investigated, but the (p,n) reaction on an enriched target isotope was found to be the best for small-sized cyclotrons. The three positron emitters ^{64}Cu, ^{124}I and ^{86}Y, which are presently in great demand, are produced via this route. Although the yield is rather low, the product is of high radionuclidic purity. Some other positron-emitting radionuclides, such as ^{55}Co, ^{76}Br, ^{89}Zr, ^{82m}Rb, ^{94m}Tc, ^{120}I, etc., are also produced via the low-energy (p,n), (p,α) or (d,n) reaction. On the other hand, the production of radionuclides ^{52}Fe, ^{73}Se, ^{83}Sr, etc. using intermediate energy (p,xn) or (d,xn) reactions needs special consideration, the nuclear data and chemical processing methods being of key importance. In a few special cases, a high intensity ^{3}He- or α-particle beam could be an added advantage. The production of some potentially interesting positron emitters via generator systems, for example ^{44}Ti/^{44}Sc, ^{72}Se/^{72}As and ^{140}Nd/^{140}Pr was also considered. The significance of new generation high power accelerators was briefly discussed.

Over the years, considerable experimental information on nuclear data for production of novel positron emitters has been accumulated. Accelerator production of radionuclides is flourishing, and therefore it would be very timely to perform data evaluation for a few selected novel positron emitters.

3.3. Status of the IAEA medical database and proposal for upgrade, F. Tárkányi

F. Tárkányi presented a summary, including a short history of evaluations, problems and drawbacks of the present nuclear reaction databases, new developments and progress in the related field and proposal for new evaluations. The databases have proved to be highly popular for medical applications which can be seen from the high number of retrievals and references in refereed journals. The reaction databases for production of diagnostic radioisotopes and monitor reactions should be completed, and recommended decay data should be added.

The following proposals were made for reactions in the different fields of application:

Monitor reactions:

- Solve the contradictions in ^{nat}Cu(p,x)^{62,63,65}Zn cross sections.
- Include the ^{nat}Cu(p,x)^{58}Co and ^{nat}Mo(p,x)^{96mg}Tc reactions.
- Upgrade ^{27}Al(p,x)^{22,24}Na ,^{27}Al(d,x)^{22,24}Na, ^{27}Al(^{3}He,x)^{22,24}Na and ^{27}Al(α,x)^{22,24}Na at high energies.
- Include ^{nat}Cu(d,x)^{62,63,65}Zn, ^{nat}Ni(d,x)^{56,57,58}Co and ^{nat}Fe(d,x)^{57}Co reactions.
- Include ^{nat}Ti(d,x)^{46}Sc reaction for higher-energy deuterons.

Production of diagnostic gamma emitters:

- Upgrade ^{124}Xe(p,2n)^{123}Cs, ^{124}Xe(p,pn)^{123}Xe reactions, and include ^{124}Xe(p,x)^{121}I side reaction.
- Include data for gamma emitters produced by neutrons: ^{98}Mo(n,γ)^{99}Mo(^{99m}Tc), ^{235}U(n,f)^{99}Mo(^{99m}Tc),…
- Include ^{100}Mo(p,2n)^{99m}Tc, ^{100}Mo(p,pn)^{99}Mo and ^{100}Mo(d,3n)^{99m}Tc, ^{100}Mo(d,p2n)^{99}Mo reactions.

Production of positron emitters

^{38}K, ^{60}Cu,^{61}Cu,^{62}Zn(^{62}Cu),^{64}Cu via ^{68}Zn(p,αn), ^{66}Ga,^{68}Ga direct, ^{72}As, ^{73}Se, ^{76}Br, ^{86}Y, ^{94m}Tc, ^{110m}In

New measurements and evaluations of the decay data of some of the medical radioisotopes may be necessary and could be done in the frame of a CRP, if proper expertise is available.

3.4. Activities of the National Metrology Institute (NMI), M.-M. Bé

M.M. Bé gave an overview of the activity of the National Metrology Institute (NMI) as well as a brief description of the international metrology chain. The first part of the presentation describes the organization of radionuclide metrology, from the ‘top’ (Bureau International des

Poids et Mesures (BIPM)) to “the user” (for example practitioners in hospital). Fluorine-18 was taken as example, with the first measurement of activity carried out by means of a “primary method’ (i.e. which does not require a calibration) – the result of this activity measurement is taken as a reference value, which is then transferred as a ‘point of calibration’ for secondary instrument such as ionization chambers (IC). When a user wants to calibrate his/her own instrument (such as activimeters in hospital), he/she sends a sample of fluorine-18 solution to NMI. The IC is used, as transfer instrument, to measure this sample; the result of activity measurement is then transmitted to the user as well as an official ‘certificate’. This example was given to highlight the need of standards at each level of the measurement chain.

The Laboratoire National Henri Becquerel (LNHB), which is the French NMI, makes use of various specific instruments to maintain and upgrade the references for activity (Becquerel) and dosimetry (Gray).

Since all methods require good knowledge of the decay data, a small group at LNHB is in charge of this activity. This group works in close cooperation with DDEP (Decay Data Evaluation Project), LNHB being one of the creators of this international working group. The DDEP was created with the objective of producing well-established decay data which can be used by the whole ionizing radiation metrology community and all the users of ionizing radiations.

The evaluations done by DDEP members, when available, are sent to LNHB for publication. In 2004, the results of the DDEP evaluations were published as a *Monographie BIPM*, under the auspices of the CCRI (Consultative Committee for Ionising Radiations). So far, five volumes have been published and the sixth is in preparation. The corresponding web site (www.nucleide.org) is also regularly updated.

The second part of the presentation was dedicated to ‘emerging nuclides’. A list of possible new radio pharmaceuticals, given by medical physicists, has been shown. However, the decay schemes for most of these nuclides are not well-known and there is no reference value in the International System of References (SIR), so their traceability cannot be assured. To improve this situation, an international exercise on Cu-64 was organized in which five European NMIs participated. First they were asked to measure the activity of a solution using all possible methods of measurement, then to send a sample to BIPM for submission to SIR, and to measure the decay data. Five results of activity measurements were sent to the SIR showing good agreement, for which then a key reference value will be established. Moreover, from the previous published decay data values and the new results obtained in this exercise, a new decay scheme was derived.

In conclusion, it was underlined that, for most of these nuclides, the decay scheme data are not well-known and there is no established traceability in the measurement hierarchy. This situation can only be solved by new studies and measurements.

3.5. High-energy accelerator production of ^{225}Ac: cross sections for ^{232}Th + p, F.M. Nortier

F. Meiring Nortier (Los Alamos National Laboratory, USA) presented the status of data for production of ^{225}Ac from thorium targets and the new measurement efforts at Los Alamos National Laboratory. While the radiotherapy isotopes ^{225}Ac and ^{213}Bi have shown tremendous cancer fighting potential, their widespread use in radiotherapy has been restricted by the limited availability of ^{225}Ac. Presently, the worldwide ^{225}Ac supply of around 1 Ci per year comes almost exclusively from two ^{229}Th sources located at Oak Ridge National Laboratory (ORNL) and the Institute for Transuranium Elements (ITU) in Karlsruhe. The anticipated growth in future ^{225}Ac demand has recently led to the investigation of a number of alternative production methods including accelerator production routes. Cross-section measurement efforts are in progress at Los Alamos National Laboratory (LANL). The work presented forms part of a wider evaluation of high energy accelerator production routes, employing intense 100-, 200- and 800-MeV proton beams and thorium targets for the large-scale production of ^{225}Ra, ^{225}Ac and ^{229}Th. Such beams are available at Los Alamos National Laboratory (LANL) and Brookhaven National Laboratory (BNL).

Experimental cross sections relevant to production of ^{225}Ac via ^{232}Th(p,x) nuclear reactions were measured. The LANL measurements at 800 MeV provide new cross section data for ^{225}Ra, ^{227}Ac, ^{223}Ra and ^{227}Th. For the energy range below 200 MeV, an up-to-date review of published nuclear cross-section data relevant to the production of ^{225}Ac and other alpha-emitting therapy isotopes such as ^{223}Ra shows that several data gaps and discrepancies exist. As an example, the present status for ^{232}Th(p,x)^{225}Ac is shown in Fig. 1. Ongoing LANL measurements using 200- and 100-MeV proton beams are expected to contribute significantly towards filling these gaps in the energy range between 100- and 200-MeV, but additional measurements below 100 MeV will be needed. A comparison of theoretical cross sections obtained using codes such as CEM, Bertini, INCL and ALICE2010 with preliminary measured data as well as existing data shows that theory overestimates the formation of the actinium isotopes while cross sections for the formation of thorium and radium isotopes are better predicted.

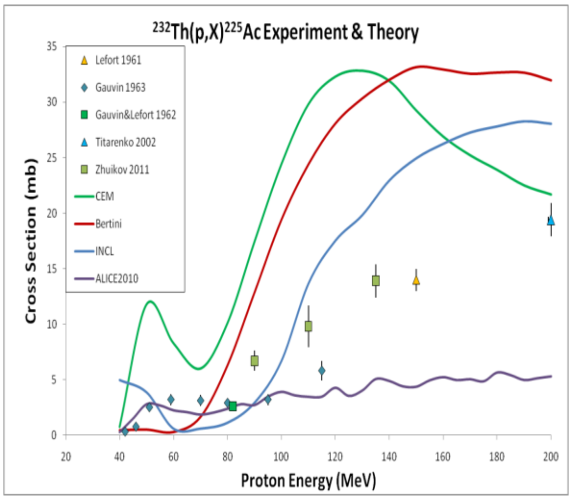

Fig.1. Comparison of existing experimental and theoretical cross sections for ^{232}Th(p,x)^{225}Ac.

3.6. Status of charged-particle induced reaction cross-section measurements by using the stacked-foil activation method, G. Kim

Guinyun Kim (Kyungpook National University, Korea) presented on overview of charged-particle induced reaction cross-section measurements by his group. Since 2005, production cross-sections of the residual radionuclides for charged-particle induced nuclear reactions have been measured up to 45 MeV by using a stacked-foil activation technique in conjunction with the azimuthally-varying field-type (AVF) MC50 cyclotron of the Korea Institute of Radiological and Medical Sciences (KIRAMS). The maximum beam energy of protons and alphas is 50 MeV while that of deuterons is 25 MeV. The results were compared with the reported experimental data as well as the theoretical calculations based on the TALYS and ALICE-IPPE codes. A summary of the published cross-section measurements for proton-induced reaction cross-sections is given in Table 1 below.

Table 1

Nuclear reaction	**Produced nuclides**	**Journal**
^{nat}Mo(p,xn)	^{99m}Tc, ^{96m,g}Tc, ^{95m}Tc, ^{95g}Tc	*J. Korean Phys. Soc.*, 48 (2006) 821
^{nat}Mo(p,xn)	^{94m}Tc, ^{94g}Tc, ^{93m}Tc, ^{93g}Tc	*J. Korean Phys. Soc.*, 50 (2007) 1518
^{nat}Zn(p,xn)	^{66,67}Ga, ^{62,65,69m}Zn, ^{61}Cu	*Nucl. Instr. Meth. B* 258 (2007) 313
^{nat}Mo(p,xn)	^{99m,96g,96m,95m,95g,94m,94g,93m,93g}Tc, ^{99,93m}Mo, ^{96,95g,90}Nb, ^{89g}Zr	*Nucl. Instr. Meth. B* 262 (2007) 171

^{nat}Zr(p,xn)	^{90,92m,95g,96}Nb, ^{88,89}Zr, ^{86,87m,87mg,88}Y	*Nucl. Instr. Meth. B* 266 (2008) 13
^{nat}W(p,xn)	^{181,182m,182g,183,184g,186}Re	*Nucl. Instr. Meth. B* 266 (2008) 1021
^{nat}Cd(p,xn)	^{107,111m,115g}Cd, ^{108m,108g,109g,110m,110,111g,113m,114m,115m,116m}In, ^{104g,105g,106m,110m,111g,113g}Ag	*Nucl. Instr. Meth. B* 266 (2008) 4877
^{nat}Ag(p,xn)	^{104g,105,106m}Ag, ^{104,107}Cd	*Nucl. Instr. Meth. B* 266 (2008) 5101
^{nat}Sn(p,xn)	^{124,122,120m,118m,117}Sb, ^{117m,113}Sn, ^{114m,111,110}In	*Nucl. Instr. Meth. B* 267 (2009) 23
^{nat}Zr(p,xn)	^{86g,87m,87g}Y, ^{88,89g}Zr, ^{90,92m}Nb	*Appl. Radiat. Isot.* 67 (2009) 1341
^{nat}Ti(p,xn)	^{48}V, ^{43,44m,44g,46,47,48}Sc	*Appl. Radiat. Isot.* 67 (2009) 1348
^{nat}Pd(p,xn)	$^{105g+m,106m}$Ag, ^{100,101}Pd, $^{100g+m,101m,105g+m}$Rh	*Nucl. Instr. Meth. B* 268 (2010) 2303
^{nat}Ni(p,xn)	$^{55,56,57,58m+g}$Co, ^{56,57}Ni	*Nucl. Instr. Meth. B* 269 (2011) 1140

Recently, production cross-sections of the residual radionuclides for the ^{nat}Fe(p,x)^{55,56,57}Co, ^{51}Cr, and ^{52,54}Mn, and ^{nat}Fe(α,x)^{55,56,57,58,61}Co, ^{56}Mn, and ^{56,57}Ni nuclear reactions were also measured. Measurements of production cross-sections of the ^{nat}Y(p,x)^{86,88,89g}Zr, ^{86g,87g,87m,88g}Y, ^{85g}Sr and ^{84g}Rb nuclear processes up to 42-MeV proton energy were also carried out at the MC-50 cyclotron. as well as production cross-sections of the residual radionuclides for the ^{nat}Fe(d,x)^{55,56,57,58}Co, ^{51}Cr, and ^{52,54,56}Mn by using 40-MeV deuterons produced at CYRIC in Tohoku University, Japan. Comparison of the results with the available experimental data as well as theoretical calculations based on the TALYS and ALICE-IPPE codes showed good agreement.

The Korea Atomic Energy Research Institute (KAERI) has proposed a high power proton linear accelerator of energy 100 MeV and successfully developed a 20 MeV drift tube linac. The 100 MeV proton linac and beam line facilities will be completed by 2012. In order to provide wide ranges of beam energies, currents and beam time, it is essential to extract a low energy beam of 20 MeV and a medium energy beam of 100 MeV, and to distribute the beams to the multi beam lines simultaneously. There are two facilities for cross-section measurements and production of radioisotopes at both 20 and 100 MeV beam lines. More measurements of proton-induced reaction cross-sections can be expected with these beam lines from 2013 onwards.

3.7. Nuclear data for medical RI production by using accelerator neutrons, Y. Nagai

Y. Nagai (Japan Atomic Energy Agency, Japan) presented an overview of neutron induced cross-section measurements relevant to the supply of ^{99m}Tc by his group. ^{99m}Tc has been widely used in nuclear medicine for diagnostics. In fact, more than 80% of all diagnostic procedures in the world are carried out every year with ^{99m}Tc-labeled tissue-specific radiopharmaceuticals. Therefore, a reliable supply of ^{99}Mo, the parent nuclide of ^{99m}Tc, is the key issue to ensure the routine application of ^{99m}Tc.

An unscheduled shutdown of two of the ^{99}Mo producing research reactors has recently caused a serious shortage of ^{99}Mo worldwide, triggering widespread discussion on the long-term supply of ^{99}Mo.

A new route of producing ^{99}Mo via ^{100}Mo(n,2n)^{99}Mo using fast neutrons from an accelerator has been proposed$^{1,2)}$. The method possesses the following characteristics: the reaction cross section is large, ~ 1.5 b at E_n ~ 14 MeV, the cross sections for radioactive waste production reactions are quite small, intense ~ 14 MeV neutrons could be obtained using a small accelerator, and ^{100}Mo sample of over 200 g can be used.

The neutron intensity within the ^{100}Mo sample is the key issue for sufficient production of ^{99}Mo by ^{100}Mo(n,2n)^{99}Mo. Recent progress in accelerator technology enables us to obtain high-flux fast neutrons. In fact, at SPIRAL2 in GANIL, neutrons with a high flux of 10^{15} n/s with a most probable energy of 14 MeV are produced by ^{nat}C(d,n) using 40 MeV 5 mA deuterons. Using the neutrons, typically, 7.1 TBq of ^{99}Mo could be obtained for a ^{100}Mo sample with a thickness of 2 cm and a radius of 2 cm (251 g ^{100}Mo) for two days irradiation at the end of irradiation. Although the specific activity of the produced ^{99}Mo is low, a method has been successfully developed to separate ^{99m}Tc of low specific activity from ^{98}Mo or ^{100}Mo using the sublimation technique.

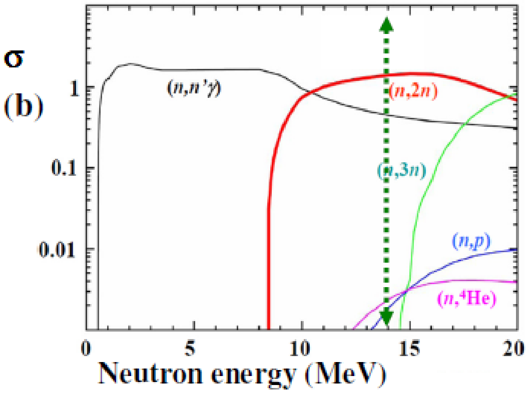

Fig.1. Cross sections of neutron induced reactions on ^{100}Mo vs neutron energy

Research and development work on ^{99}Mo/^{99m}Tc is in progress using accelerator-produced neutrons from ^{3}H(d,n)^{4}He.

References:
[1] Y. Nagai and Y. Hatsukawa: J. Phys. Soc. Japan, **78** (2009) 033201.
[2] F. Minato and Y. Nagai: J. Phys. Soc. Japan, **79** (2010) 093201.

ANNEX A

Consultants’ Meeting on

“Improvements in Charged-particle Monitor Reactions and Nuclear Data for Medical Isotope Production”

IAEA Headquarters, Vienna, Austria
21 – 24 June 2011

Meeting Room M0E60

Preliminary AGENDA

Tuesday, 21 June

08:30 - 09:30	**Registration** (IAEA Registration desk, Gate 1)
09:30 - 10:15	**Opening Session**
	Welcoming address – Meera Venkatesh (DIR-NAPC) Introduction – Roberto Capote Noy Election of Chairman and Rapporteur Adoption of Agenda
10:15 - 12:15	**Presentations by participants**
12:15 – 12:30	Administrative matters
	Coffee break as needed
12:30 – 14:00	***Lunch***
14:00 – 18:00	**Presentations by participants (cont’d)**
	Coffee break as needed
19:00	***Dinner at a Restaurant downtown (see separate information)***

Wednesday, 22 June

09:00 - 12:30	**Presentations by participants (cont’d)**
	Coffee break as needed
12:30 – 14:00	***Lunch***
14:00 – 18:00	**Presentations by participants (cont’d)**
	Coffee break as needed

Thursday, 23 June

09:00 - 17:00 **Definition of the scope and deliverables of the future CRP**

a) Beam monitor reactions and decay data of reference nuclides

b) Cross sections and decay data for medical isotope production

Coffee and lunch break(s) in between

Friday, 24 June

09:00 - 16:00	**Drafting of the meeting summary report**
	Coffee and lunch break(s) in between
16:00	**Closing of the meeting**

Consultants' Meeting
"Improvements in Charged-particle Monitor Reactions and Nuclear Data for Medical Isotope Productions"

IAEA Headquarters, Vienna, Austria
21 – 24 June 2011

LIST OF PARTICIPANTS

FRANCE

Marie-Martine BÉ
Laboratoire National Henri Becquerel
CEA-Centre d'Etudes de Saclay
91191 Gif-sur-Yvette Cedex
Tel. + 33-1-69084641
E-mail: Marie-Martine.Be@cea.fr

GERMANY

Syed M. QAIM (Chair)
Institut fuer Nuklearchemie
Forschungszentrum Juelich
Leo-Brandt-Straße
Postfach 1913
52425 Juelich
Tel. +49 2461-61-3282
E-mail: s.m.qaim@fz-juelich.de

HUNGARY

Ferenc TARKANYI
Cyclotron Department
Institute of Nuclear Research
Hungarian Academy of Sciences
Bem ter 18/c
P.O. Box 51
4001 Debrecen
Tel: + 36 52-509 200
E-mail: tarkanyi@atomki.hu

JAPAN

Yasuki NAGAI
Research Center for Nuclear Physics
Osaka University
Mihogaoka, 10-1
Ibaraki, Osaka 567-0047
Tel. +
E-Mail: nagai@rcnp.osaka-u.ac.jp

KOREA

Guinyun KIM
Kyungpook National University
High Energy Physics Institute
Daegu 702-701
Tel. +
E-mail: gnkim@knu.ac.kr

USA

F.Meiring NORTIER
Los Alamos National Laboratory
Chemistry Division
Mail Stop J519
Los Alamos NM 87545
Tel. +1 505-667-9501
E-mail: meiring@lanl.gov

IAEA

Roberto CAPOTE NOY
NAPC Nuclear Data Section
Vienna International Centre
PO Box 100
1400 Vienna
Austria
Tel. +43-1-2600-21713
E-Mail: r.capotenoy@iaea.org

Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre, P.O. Box 100
A-1400 Vienna
Austria

e-mail: services@iaeand.iaea.org
fax: (43-1) 26007
telephone: (43-1) 2600-21710
Web: http://www-nds.iaea.org