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Nuclear Data for the Production of Therapeutic Radionuclides

Summary Report of Third Research Coordination Meeting

IAEA Headquarters
Vienna, Austria
29 May – 2 June 2006

Prepared by

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August 2006

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Abstract

A summary is given of the Third Research Coordination Meeting on Nuclear Data for the Production of Therapeutic Radionuclides. The new library of evaluated cross-section will cover reactor and accelerator production of therapeutic radionuclides to appropriate specific activities and purity, along with the relevant decay data. A few new reactions were added at this meeting. Technical discussions and the resulting work plan to conclude the data evaluation activities are summarized for every reaction path. Timescales and agreed actions to deliver the database and Technical Report are also given.

August 2006

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SUMMARY OF THE MEETING

Cancer management has become a major medical and economic issue because of the ever growing incidence of this disease worldwide. This has simultaneously given rise to an increasing need to generate radioisotopes for cancer treatment which represents a scientifically well-established field of research and development. Medical applications of nuclear radiation are of considerable interest to the IAEA. The number of countries that possess cyclotrons and accelerators able to produce radioisotopes for both diagnostic and therapeutic purposes has greatly risen in recent years. Furthermore, reactors are still widely employed to produce radioisotopes for many different applications including nuclear medicine. Those needs were addressed by a Coordinated Research Project (CRP) on "Charged Particle Cross-Section Database for Medical Radioisotope Production: Diagnostic Radioisotopes and Monitor Reactions" which concluded in 2002 with the publication of **IAEA-TECDOC-1211**. A new Coordinated Research Project on "Nuclear Data for the Production of Therapeutic Radionuclides" started in 2003.

The first Research Co-ordination Meeting (RCM) on Nuclear Data for the Production of Therapeutic Radionuclides was held at the IAEA Headquarters in Vienna, Austria, from 25 to 27 June 2003. A co-ordinated programme of work was agreed among the participants, leading to several additional actions to be undertaken. Technical discussions and the resulting work plan of the Coordinated Research Project were summarized in **INDC(NDS)-444.**

The second RCM of this CRP was held at the IAEA Headquarters in Vienna, Austria, from 15 to 19 November 2004. The work accomplished in the first two years of the CRP was critically reviewed, and the scope of the CRP was expanded to cover a number of new reactions of interest. Technical discussions and the resulting work plan of the Coordinated Research Project were summarized in **INDC(NDS)-465**.

A third and final RCM on Nuclear Data for the Production of Therapeutic Radionuclides was held at the IAEA Headquarters in Vienna, Austria, from 29 May to 2 June 2006. The primary aims of this meeting were to review the work undertaken during the five years of the CRP, discuss scientific and technical matters related to the subject, coordinate the remaining tasks, and expand the scope of the CRP to cover a few new reactions of interest and to assess assigned responsibilities. It was very important to define a precise time scale to deliver the desired outputs.

Eight CRP participants and two external observers attended the third RCM. Prof. S.M. Qaim of the Institut für Nuklearchemie, Forschungszentrum Jülich, Germany was elected Chairman of the meeting; J.-Ch. Sublet, from CEA Cadarache, France, agreed to act as rapporteur. The IAEA was represented by A. L. Nichols (Head, Nuclear Data Section) and R. Capote Noy, who served as Scientific Secretary. The approved Agenda is attached (Appendix 1), as well as a list of participants and their affiliations (Appendix 2).

A. L. Nichols welcomed the participants, and emphasized the significance of their role in the development and production of this important database for therapeutic applications. Whether nuclear data for the production of diagnostic and therapeutic radionuclides exist or not, and whether they are poorly or well known, one should acknowledge the fact that these isotopes have been produced and used in nuclear medicine treatment for many years. The improved quality of the nuclear data that will be generated during this CRP will make their production much more efficient and effective, and should also enhance their quality through improved purity.

There are a significant number of radioisotopes in use or being proposed for therapeutic applications. As a consequence of the work undertaken during the course of this CRP, the resulting completeness and accuracy of the nuclear data for the production of these nuclides to appropriate specific activities and purity along with the re-definition of their decay data should be adequate for their safe and efficient medical applications. Moreover, the data produced in this CRP will help to define strategies for the production of radioisotopes at cyclotrons, as is currently being studied by an expert group within the Industrial Applications and Chemistry Section of the IAEA Division of Physical and Chemical Sciences.

The radioisotopes to be considered in the CRP have been were divided into two categories:

- Therapeutic radioisotopes that have established clinical uses – ***Established Radioisotopes.***
- Less-commonly used but potentially interesting radioisotopes for which medical applications have been demonstrated – ***Emerging Radioisotopes.***

Experimental data compilations, selection and final evaluations for each of the reactions were extensively discussed during the meeting. The recommendations for both established and emerging radionuclides, and validation/testing of the cross-section library are summarized below.

Established Radionuclides

Radionuclide	Production Route	Responsibility	R/A *
^{32}P	^{31}P(n, γ)	Choi	R

*R = Reactor, A = Accelerator

Phosphorus-32 decay scheme is simple. JENDL-3.3 cross-section file seems to be the best at low and intermediate energies. At thermal energies all the data libraries agreed well with the recommended Mughabghab value. The high-energy part of the JENDL-3.3 evaluation neither fits the experimental 14-MeV data points, nor systematics (0.433 mb). Therefore, resonance parameters were taken from JENDL-3.3 and high energy from TALYS calculations using local OMP. Good agreement is achieved with experimental data.

^{32}P	^{32}S(n,p)	Qaim	R,A

The (n,p) data were taken from the EXFOR database and analysed; some of the data were deselected. Theoretical calculations gave very discrepant results. Adoption of the IRDF-2002 evaluation is recommended. Integral measurement in 14-MeV d(Be) spectrum gave a C/E value of 1.1.

^{89}Sr	^{89}Y(n,p)	Qaim	R,A

The (n,p) data (which depend on difficult beta counting) from the EXFOR database have been analyzed; a few points seemed too low and were deselected. EMPIRE and STAPRE calculations have been performed without much noticeable differences. Either calculation is recommended. Integral measurement in 14-MeV d(Be) spectrum gave a C/E value of 1.1.

^{89}Sr	^{88}Sr(n,γ)	Betak	R

The resonance region has been well measured. Only one old measurement exists around 1 MeV. The TALYS and EMPIRE model calculations and shapes do not agree with each other. TALYS is recommended, because these data fits the value from the systematics around 14 MeV better. Measurements above the resonance region are required to ascertain the calculation.

^{90}Y	^{235}U(n,f) ^{90}Sr$\rightarrow$ ^{90}Y generator	Sublet	R

This reaction is the route of production of the very commonly used ^{90}Y isotope. The cumulative and independent yields are provided together with their uncertainties. The half-life of ^{89}Sr of 50 days is much shorter than that of ^{90}Sr, causing no serious disturbance in the preparation of the generator. Experimental chain yield measurements are provided as well.

^{90}Y	$^{89}Y(n,\gamma)$	Carlson	R

The ENDF/B-VI file contains more resonances but the MLBW JENDL-3.3 file 2 is preferred. MLBW makes too much of a hole before the first resonance, and the RM flag needs to be considered. The 20% differences in integrated values (fission averaged) need to be explained.

^{90}Y	$^{90}Zr(n,p)$	Carlson	R

A new 2005 evaluation from Obninsk (Zolotarev) to update the dosimetry file IRDF-2002 is recommended.

^{103}Pd	$^{102}Pd(n,\gamma)$	Carlson	R

The JENDL-3.3 file has been taken as a starting point, and some resonance parameters adjusted. Pd-102 is only around 1%, and enriched materials may be needed. Some more work needs to be done to reduce the discrepancy with the resonance integral measurements.

^{103}Pd	$^{103}Rh(p,n)$	Qaim, Tarkanyi, Ignatyuk	A

All the data have already been analysed and finalised. X-ray counting was considered to be reliable (gamma counting is unreliable, and measurements based on this approach were deselected). Pade fitting with uncertainty needs to be carried out on the newly selected data points of Sudar of 2002. The intensity of the weak 357-keV gamma line needs to be accurately determined. The data of the $^{103}Rh(p,pn)$ reaction should be compiled by Tarkanyi and fitted by Ignatyuk.

^{103}Pd	$^{103}Rh(d,2n)$	Tarkanyi, Ignatyuk	A

Only the X-ray measurements will be selected prior to Pade fitting and new model calculations. The gamma measurements are always too high. The (d,p2n) reaction was measured for both the ground and first isomer (2.9 years and 207 days); the data will be sent by Tarkanyi to Ignatyuk for fitting and model calculation.

^{125}I	$^{124}Xe(n,\gamma)^{125}Xe \rightarrow {}^{125}I$	Betak, Carlson	R

Model calculation (TALYS and EMPIRE) are in good agreement, but in the PEQ region. The JENDL-3.3 resonance region has been taken as a starting point, with a slight variation to bring the RI close to the only measurement made. ^{125}I is used extensively in brachytherapy and radioimmunoassay. $^{125}I(n, \gamma)$ needs to be evaluated as well (Carlson).

^{131}I	$^{130}Te(n,\gamma)\ ^{131}Te \rightarrow {}^{131}I$	Choi	R

The decay scheme has been analysed. Two final states are produced. Most library cross-sections are given only for the total. A new evaluation has been performed merging a modified JENDL-3.3 file 2 with an optimized TALYS model calculation and accounting for the experimental data selected including energy-dependent branching ratio information. The influence of the threshold reaction data around 14 MeV needs to be checked. Te is deformed; the influence of the deformation should be checked.

^{131}I	^{235}U(n,f)	Sublet	R

This is one of the most important therapeutic radioisotopes produced and used worldwide, and is an extremely well known fission product for which the yield has been well measured.

^{137}Cs	^{235}U(n,f)	Sublet	R

^{137}Cs (gamma and beta emitter) is used in brachytherapy. This is an extremely well known fission product, for which the yield has been well measured.

^{153}Sm	^{152}Sm(n,γ)	Betak, Carlson	R

Calculations using both EMPIRE and TALYS are in good agreement. The BROND-2.2 or ENDF/B-VII evaluations will be checked and a recommendation made.

^{153}Sm	^{153}Eu(n,p)	Qaim	R,A

^{153}Eu(n,p)^{153}Sm has been analysed by the Jülich group, and a model calculation has been performed. A spallation neutron source may make use of this reaction. The STAPRE calculation is recommended. Integral measurement in 14-MeV d(Be) spectrum gave a C/E value of 1.15. Qaim to send the data and the STAPRE results to Sublet.

^{186}Re	^{185}Re(n,γ)	Sublet	R

The existing evaluations have been analysed, demonstrating good thermal and resonance integral agreements between evaluations and experimental measurements. A very long-lived isomer exists, decaying by isomeric transition only. Isomeric cross-sections at thermal energy are given in the Karlsruhe chart of nuclides.

^{186}Re	^{186}W(p,n)	Tarkanyi, Ignatyuk	A

EMPIRE and GNASH calculations have been performed. Zhang data were corrected by a factor of 2 on the basis of simultaneously measured reactions. The Pade fit is accepted but there is a need for cleaner measurements of this reaction.

^{186}Re	^{186}W(d,2n)	Tarkanyi, Ignatyuk	A

Measurements have been carried out, and Pade fitting is considered best for this channel. The tail above 20 MeV from EMPIRE seems too low and may be related to shortcomings in the description of direct or pre-equilibrium processes. The importance of break-up effects in high Z materials may explain the overestimation at the peak.

The isomeric branching ratio is 60% to the first isomer at the peak for the (d,2n), fading to 30% thereafter. The ratio is 30% in the (p,n) reaction. This means that this route of production will lead to higher production of the long-lived isomer compared to (p,n).

^{188}Re	$^{186}W(n,\gamma)\rightarrow{}^{187}W(n,\gamma)^{188}W\rightarrow$ $\rightarrow{}^{188}Re$ generator	Sublet	R

This is an important channel for the production of ^{188}Re in no carrier added form. The first capture reaction has already been evaluated and validated by both differential and integral measurements. The second reaction is based on theoretical model calculations, with only one resonance integral and a thermal experimental value. The 10% uncertainty in the $^{187}W(n,\gamma)$ cross-section of 70 barn at thermal energy is acceptable for production purposes.

^{188}Re	$^{187}Re(n,\gamma)$	Carlson	R

ENDF/B-VI agrees well with differential measurements, thermal cross-section and resonance integral and contains covariance data. Comparison with ENDF/B-VII should be made before final recommendations.

^{192}Ir	$^{191}Ir(n,\gamma)$	Choi	R

Some questions are raised about the spin and the energy of the second isomeric state. TALYS calculation has been performed in the high energy region. Measurements are recommended for the level scheme.

^{192}Ir	$^{192}Os(p,n)^{192}Ir$	Qaim, Ignatyuk	A

The excitation function has been measured using thin samples. Model calculations have been performed as well. Comparison with reactor and cyclotron production has been performed, pointing out a clear advantage of the reactor production route in terms of yield and impurity level. More work may be undertaken on the description of the isomeric branching ratio in general – one always has to rely on measurements.

^{192}Ir	$^{192}Os(d,2n)^{192}Ir$	Qaim, Tarkanyi, Ignatyuk	A

The excitation function has been measured using thin samples. Model calculations have been performed as well. Pade fitting needs to be performed. The maximum of the (d,2n) cross-section is four times higher than for the (p,n) reaction.

Emerging Radionuclides

Radionuclide	Production route	Responsibility	R/A/D *
^{64}Cu	$^{63}Cu(n,\gamma)$	Sublet	R

*R = Reactor, A = Accelerator, D = Decay

This is one of the most important emerging therapeutic radionuclides that permits a combination of therapy and positron emission tomography. A new decay scheme has been evaluated at Jülich 17.8% β^+, 38.4 β^- and 43.8% electron capture, 0.54% for the 1346-kev gamma line. This reaction is still occasionally used. A high flux reactor can lead to reasonable specific activity, although the preferable production route is now by cyclotron.

^{64}Cu	$^{64}Ni(p,n)$	Qaim, Ignatyuk	A

Experimental data selection has been made; Levkovskii data set appears too high and was deselected. All other values have been raised by 7% to account for the change in the positron branching. A 15% uncertainty is assigned to all the Blaser (1951) data that contained none. New Pade fitting has to be done. Model calculations have been made and show reasonable agreement with the experimental data.

^{64}Cu	$^{64}Ni(d,2n)$	Nortier,Tarkanyi, Ignatyuk	A

One set of experimental data is available (Zweit et al. 1991). Thick target yield measurement by the same authors disagrees with the yields calculated from the excitation function. Preliminary data on the same reaction from Debrecen were presented. Further analysis is necessary, including an upward adjustment of 7% of the Zweit data. The data should be compared with the completed model calculations. Pade fitting must be undertaken after the Debrecen data are finally analysed.

^{64}Cu	Zn(d,x)	Nortier, Ignatyuk	A

Hilgers' values need to be raised by 7% and the Groppi and Tarkanyi data corrected as well following the new decay data values. The $^{66}Zn(d,\alpha)$ data of Hilgers should be normalized to natural Zn data, but only up to 10 MeV because of the onset of the (d,2p) reaction on ^{64}Zn. Hilgers' natural Zn data below 8 MeV should be deselected. Pade fitting needs to be carried out. An integral measurement around 12 MeV may be useful. The ^{67}Cu impurity level has been considered, and the activity ratio needs to be calculated.

^{64}Cu	$^{68}Zn(p,x)$	Nortier, Ignatyuk	A

Three sets of data exist, and all need to be corrected for decay intensity. In the case of the Szelencenyi data, correction for both gamma intensity and positron emission need to be made. The five points by Hilgers between 22 and 35 MeV should not be considered in doing the Pade fitting. ALICE-IPPE calculation agrees well with the experimental data. The energy used for production should be no more than 40 MeV, because of the ^{67}Cu impurity production.

^{64}Cu	$^{64}Zn(n,p)$	Choi	R

Qaim compiled and deselected some data. Zolotarev performed a new evaluation in 2006 to update IRDF-2002. A relook at the evaluation could be necessary, particularly from 5 to 12 MeV. Spectrum-averaged integral data agree within 10%. Using EAF-2003, the 14-MeV d(Be) source measured value for C/E is 6% higher.

^{67}Cu	$^{67}Zn(n,p)$	Choi	R

A lot of experimental data seem to be wrong, Qaim performed compilation and deselection of some of the data. A positive Q-value reaction for which experimental data exist at thermal energy. EAF-2005 1/E needs to be included. Sublet will give the file to Choi.

^{67}Cu	$^{68}Zn(p,2p)$	Nortier, Tarkanyi Ignatyuk	A

Six data sets are available up to 200 MeV; only one of them measured on natural Zn. All measurements made by Levkovskii with protons need to be lowered by 20%. McGee data have been corrected by Nortier with an up to date IAEA monitor. Two sets of data have been deselected (error greater than 25%). Tarkanyi to send new experimental data (Cape Town, Debrecen collaboration) to Nortier for evaluation; then Pade fitting by Ignatyuk will be carried out. Production of ^{64}Cu as impurity via ^{68}Zn (p,αn) and $^{68}Zn(p,2p3n)$ reactions was considered. Calculation of the impurity yield ratio must be made. Theoretical calculations were carried out, but the results do not describe the cross-section well.

^{67}Cu	$^{70}Zn(p,\alpha)$	Qaim, Ignatyuk	A

The last two points should not be taken into account. Pade fitting is good and accepted.

^{67}Ga	$^{68}Zn(p,2n)$,$^{67}Zn(p,n)$	Capote	A

This radionuclide has been in use as a diagnostic SPECT nuclide for some time. As an almost pure Auger electron emitter with a favourable half-life of 3.2 days, ^{67}Ga is also finding increasing use in metabolic therapy. This radionuclide has already been previously evaluated for diagnostic purpose (earlier CRP).

^{86}Y	$^{86}Sr(p,n)$	Qaim, Ignatyuk	A

This is an important positron-emitting radionuclide for quantification of dosimetry in internal radiotherapy with ^{90}Y. Two sets of experimental values exist, and the isomeric state cross-section has been calculated. Pade fitting needs to be made.

^{105}Rh	$^{104}Ru(n,\gamma)^{105}Ru \rightarrow {}^{105}Rh$	Choi	R

The decay scheme looks to be good. The evaluation contains JENDL unresolved resonance range with TALYS calculations above this range agreeing well with the experimental data.

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

This radionuclide has been in use as a diagnostic SPECT nuclide for some time. However, as an almost pure Auger electron emitter with a favourable half-life of 2.8 days, ^{111}In is also finding increasing use in metabolic therapy. ^{111}In has already been evaluated for diagnostic purpose (earlier CRP).

^{114m}In	$^{114}Cd(p,n)$	Tarkanyi, Ignatyuk	A

New data and compilation were reported by the Debrecen group. Theoretical calculations with EMPIRE and GNASH agree well with the data. Pade fitting has been carried out and is recommended.

^{114m}In	$^{116}Cd(p,3n)$	Tarkanyi, Ignatyuk	A

New data and compilation were reported by the Debrecen group. Theoretical calculations with EMPIRE and GNASH agree surprisingly well with the data. The experimental data are good; Pade fit exists and is recommended.

^{114m}In	$^{114}Cd(d,2n)$	Tarkanyi, Ignatyuk	A

New data and compilation were reported by the Debrecen group. Model calculations with GNASH and EMPIRE show higher cross-sections than the experimental data. A Pade fitting is recommended for the yield calculation.

^{114m}In	$^{113}In(n, \gamma)$	Sublet	R

A new evaluation – the branching ratio needs to be renormalized (m/(m+g)) to the experimental data to account for the energy dependence.

^{124}I	$^{124}Te(p,n)$	Qaim, Tarkanyi	A

One of the most important emerging therapeutic radionuclides that allows a combination of therapy and positron emission tomography. This reaction is the best method for the production of ^{124}I. An evaluation has been completed, and new fitting and yield calculated. The recommended data are available and need to be included. There was some discrepancy concerning the positron branching that has now been settled with a new ratio of 0.22 +/- 1%, now confirmed.

^{124}I	$^{124}Te(d,2n)$	Nortier, Ignatyuk	A

Two sets of experimental data exist from Jülich and Brookhaven. Original Brookhaven cross-section data are wrong, and were re-calculated from the reported thin target yield values. Both data sets can be accepted. Pade fitting is recommended up to 20 MeV. Because of the ^{125}I impurity, the $^{124}Te(d,n)$ reaction should be considered and target yield ratio must be calculated.

^{124}I	$^{125}Te(p,2n)$	Nortier, Ignatyuk	A

Only one data set was recently measured (2001) and is available. $^{125}Te(p,2n)$ reaction seems to be the best from a yield point of view. The ^{125}I impurity was considered, and the thick target yield ratio must be calculated. The data set is supported by ALICE, GNASH and EMPIRE model calculations.

^{125}I	$^{124}Te(d,n)$	Nortier, Ignatyuk	A

This route is important for consideration of the impurity level in ^{124}I via the (d,2n) reaction. Compilation has been completed, and data evaluation and Pade fit are needed.

^{125}I	$^{125}Te(p,n)$	Nortier, Ignatyuk	A

This route is important for consideration of the impurity level in ^{124}I via the (p,2n) reaction. Compilation has been completed, and data evaluation and Pade fit are needed.

^{149}Pm	$^{148}Nd(n,\gamma)^{149}Nd\rightarrow{}^{149}Pm$	Carlson	R

The final recommendation awaits the comparison of the JENDL-3.3 evaluation with ENDF/B-VII.

^{166}Ho	$^{165}Ho(n,\gamma)$	Betak	R

Two evaluated files (ENDF/B-VI and JEFF-3.1) are in good agreement in the low-energy region, but significant differences occur in the high-energy range. Model calculations by TALYS and EMPIRE have been performed and will be merged with the low energy data. The long-lived isomer cross-sections have been calculated. The (m/m+g) ratio is around 0.07, increasing to 0.3 above 1 MeV. EXFOR entry 22612003 needs to be corrected.

^{166}Ho	$^{164}Dy(n,\gamma)\rightarrow{}^{165}Dy(n,\gamma)\rightarrow$ $\rightarrow{}^{166}Dy\rightarrow{}^{166}Ho$	Sublet	R

For ^{164}Dy, there are discrepancies in MeV region for the total and ground cross-section sets. A recommendation will be made once the experimental data are selected. Fawcett data need to be checked. The second capture channel data are available.

^{169}Yb	$^{168}Yb(n,\gamma)$	Sublet	R

This is an Auger electron emitter that is gaining interest. The capture cross-section looks good and agrees with the latest Mughabghab recommendations.

^{169}Yb	^{169}Tm(p,n)	Qaim, Ignatyuk	A

The measurements were completed in 2004 as collaboration between Jülich and Debrecen, and evaluation has been completed. Theoretical calculations agree well with the data. Pade fit is accepted.

^{169}Yb	^{169}Tm(d,2n)	Tarkanyi, Ignatyuk	A

The measurements were completed in 2006 as collaboration between Jülich and Debrecen, and evaluation has been completed. Theoretical calculations disagree with the data by a factor of two. Pade fit is accepted up to 20 MeV. The expected yield of ^{169}Yb will be much higher than for the (p,n) reaction.

^{177}Lu	^{176}Yb(n,γ)^{177}Yb$\rightarrow$ ^{177}Lu	Sublet	R

This β^- emitting radioisotope is used in palliative therapy via interstitial implantation as a liquid gel injection. The existing data have been assessed, but the reaction rate is relatively low.

^{177}Lu	^{176}Yb(d,x)^{177}Lu	Tarkanyi, Ignatyuk	A

A new measurement has been performed in Brussels. Data analysis and Pade fitting should be carried out for both the (d,p) and (d,n) channels. Independent and cumulative yield calculations need to be made.

^{177}Lu	^{176}Lu(n,γ)	Sublet	R

The existing data have been assessed and an evaluation selected for both states, although the other two routes of production are better because of the carrier-free nature of the product.

^{211}At	^{209}Bi(α,2n)	Tarkanyi, Ignatyuk	A

New measurements show excellent agreement with older studies undertaken in 1949-2001. This isotope is very much in demand but production and chemistry are difficult. The experimental cross-section data for the (α,3n) reaction were compiled and a Pade fitting should be made up to 40 MeV. This reaction is important for characterising the impurity level. One integral measurement has been completed in Ispra at 29 MeV for the (α,2n) reaction leading to good agreement with the evaluated cross-section data.

^{213}Bi	decay of ^{225}Ac	Carlson	D

The JEFF-3.1 decay data are recommended.

^{225}Ac	$^{226}Ra(p,2n)$	Menapace, Capote	A

A new set of experimental data exist, published in 2005 (Applied Radiation and Isotopes). ALICE and EMPIRE calculations agree well. The uncertainty in the energy of the experimental points must be accounted for. The results of model calculation are recommended.

^{225}Ac	Decay of $^{233}U \rightarrow {}^{229}Th$	Carlson	R,D

The JEFF-3.1 decay data are recommended. Although complex, the high flux reactor route of production may be considered.

COMMENTS AND RECOMMENDATIONS

Transmission of data

Neutron data

All final neutron channel results (Betak, Choi, Carlson, Qaim) and files in point-wise ENDF-6 format will be transmitted to Sublet as soon as possible, and no later than the end of September. Sublet will then send the ENDF-6 formatted file to the IAEA Nuclear Data Section (NDS). These parameters are very important in determining integral quantities that may be extremely sensitive to the integration limits; therefore, the evaluator analysing experimental data and comparing the calculated values should be careful in the interpretation of results. Default input decks for INTER (ENDF utility code) or ENDVER could be used.

Charged-particle data

All charged-particle results should be sent to Tarkanyi as soon as possible, and no later than the beginning of September. Tarkanyi will collate and forward these data to Obninsk for fitting purposes. Obninsk will send the fitted data back to Tarkanyi for yield calculations prior to Tarkanyi transmitting the fitted curves and calculated yields to the other compilers (Nortier and Qaim) for cross checking of the evaluated curves and calculated yields. NDS will prepare and distribute the ENDF-6 formatted files from the selected data.

Decay data

Decay characteristics of every agreed radionuclide needs to be compiled by each evaluator and referenced: half-life, decay mode, average and end-point energies, gamma-ray energies and emission probabilities, Auger and X-ray emissions from MIRD (standard for treatment planning, and available on the IAEA web), ICRU, etc. The data file format will be ENDF-6.

Established radionuclides

^{103}Pd, 357-keV gamma-ray intensity needs to be checked

^{192m}Ir, spin and energy need to be defined

Emerging radionuclides
^{64}Cu, Julich measurements resolved the observed problem
^{124}I, positron emission problem, measured again at Julich at 22 +/- 0.5%
^{211}At, the weak gamma line intensity (687 keV) needs to be confirmed

Uncertainties

The uncertainty data of each evaluated neutron file will be provided by each evaluation in ENDF MF-33 format. Even a simple variance representation would be accepted.

For charged-particle reactions, the uncertainty estimation of the fitted curve will be given in 3 to 4 groups format. NDS will format.

Impurity contamination
When applicable, thin target yield ratios will be presented.

Validation

Where possible, neutron data validation has been carried out using the available in the literature such as resonance integrals, ^{252}Cf spectrum, d(Be) spectrum and spectrum-averaged and integral experiments. Part of the experimental validation of the (n,p) reactions of this CRP was recently performed using the 14-MeV d(Be) source at Jülich.

Where possible, charged-particle data have been validated. Further validation may be recommended in the final report.

Capote will update the dedicated Web site (www-nds.iaea.org/radionuclides/) with online data and report access.

Expected outputs of CRP

A few additional reactions have been added to the scope of this CRP, accounting for the latest developments and the required purity of some radionuclides.

- electronic database for use in the production of therapeutic radionuclides – radionuclide symbols, production route and validated and evaluated cross-sections as a function of energy, decay data (half-lives, beta-decay energy spectrum, gamma-ray emission probabilities, Auger electron spectra, etc); data in ENDF-6 format,
- printed version of database,
- TRS report,
- IAEA-NDS Worldwide Web online access to database, and numerical data on CD on request

Time-scale and tasks toward the TRS document

A new technical document should be written (IAEA Technical Report Series). The layout and editorial requirements will be distributed to the CRP participants by the NDS. The recommended document structure and responsible person for each part follows;

1) Introduction, Review (Qaim)

Every chapter will be split into reactor and accelerator production.

2) Data collection, selection and validation
   - Accelerator (Nortier, Tarkanyi, Qaim)
   - Reactor (Choi, Betak, Sublet, Carlson)

3) Pade fit and uncertainty (Ignatyuk)

4) Uncertainty of neutron data (Choi, Carlson, Sublet)

5) New measurements (Qaim, Tarkanyi)

6) Nuclear model calculations (Capote, Ignatyuk, Betak for TALYS)

   a) Neutron induced: Sublet, Betak, Capote, Carlson, Choi, Qaim

   b) Charged particle: Tarkanyi, Capote, Ignatyuk, Menapace, Nortier, Qaim, Scholten, Ignatyuk, Takacs

Deadline for delivery of recommended data: 15 November 2006

Full contribution deadline: 28 February 2007

Word documents, Excel file Postscript and Window Metafile for figures are recommended. Online document will be in colour but hardcopy in black and white.

For charged-particle reactions the structure should be as follows:

1) Application and importance of isotopes
2) Data selection where applicable
3) Figures
   a) all experimental data
   b) selected/corrected experimental data, and model calculations,
   c) selected/corrected experimental data, and recommended curve with uncertainties
   d) thick target yields
   e) impurity level

For neutron-induced reactions the structure should be as follows:

1) Application and importance of isotopes
2) Data selection where applicable
3) Figures: one graph per page per reaction, and a table containing the integral quantities.

The selected experimental data must be supplied to the agency as EXFOR lists or c4 files if they exist. The (n,p) cross-section figures should be in a similar form to the charged-particle figures.

Additional points of note

All participants need to supply the Agency with a list of all their publications and presentations respective to this CRP since 2002.

The following conferences are relevant to the CRP, and suitable papers could be prepared and presented on behalf of this CRP (abstracts should be sent to NDS secretary):

- Targetry workshop in Cambridge, Tarkanyi-Nortier should submit an extended abstract (deadline 14th July),
- NEMEA-3, Bulgaria, October 2006, Qaim has been invited,
- ND-2007, Nice, April 2007, NDS (Capote) is encouraged to present the CRP at this conference,
- Radiopharmaceutical meeting in Aachen, April 2007, ISRS2007,
- 6 ICI, Republic of Korea, May 2008, Choi should represent the CRP.

Appendix 1

AGENDA

International Atomic Energy Agency

Third Research Coordination Meeting on
"Nuclear Data for Production of Therapeutic Radionuclides"

IAEA Headquarters, Vienna, Austria
29 May – 2 June 2006
Meeting Room A2774

Monday, 29 May

08:30 - 09:30 **Registration** (IAEA Registration desk, Gate 1)

9:30 - 10:00 **Opening Session**

Welcoming address - A. Nichols, Section Head, IAEA Nuclear Data Section
Election of Chairman and Rapporteur
Discussion and Adoption of Agenda (Chairman)

10:00 - 11:00 **Administrative and Financial Matters related to participants**

Coffee break

11:00 - 12:15 **Session 1: Presentations by participants and discussions**
(20 minutes for each presentation and 5 minutes for discussion)

1. *Measurement and standardisation of nuclear reaction cross section data for production of some therapeutic radionuclides*, **S.M. Qaim**, Institut für Nuklearchemie, Forschungszentrum Jülich, Germany
2. *New cross-section data for accelerator-produced therapeutic radioisotopes: Experiments and data evaluations by the ATOMKI group*, **F. Tárkányi,** Institute of Nuclear Research of the Hungarian Academy of Sciences, ATOMKI, Debrecen, Hungary
3. *Experimental Nuclear Data Evaluations by the LANL Group*, **F.M. Nortier**, Los Alamos National Laboratory, C-INC: Isotopes and Nuclear, Los Alamos, USA.

12:15 - 13:40 **Lunch**

13:40 - 15:20 **Session 1: Presentations by participants and discussions (cont.)**
(20 minutes for each presentation and 5 minutes for discussion)

4. *Review of Selected Cross-Sections and Fission Yields for Production of Emerging Therapeutic Radionuclides,* **J.-Ch. Sublet,** CEA, France
5. *Calculation and evaluation of nuclear reaction cross sections for production of therapeutic radionuclides*, **A.V. Ignatyuk**, Institute of Physics and Power Engineering, Obninsk, Russia
6. *Production cross sections and decay properties of several radionuclides with therapeutic applications,* **B. Carlson**, Depto. de Física – IEF, Instituto Tecnológico de Aeronáutica, Brazil
7. *Possible production of selected therapeutic radioisotopes of A>80 using the (n, γ) reactions with fast neutrons,* **E. Běták,** Institute of Physics, Slovak Academy of Sciences, Slovakia.

15:20 - 15:50 **Coffee break**

15:50 - 17:30 **Session 1: Presentations by participants and discussions (cont.)**
(20 minutes for each presentation and 5 minutes for discussion)

8. *Neutron (n, γ) cross section and decay data for* ^{32}P*,* ^{89}Sr*,* ^{131}I*,* ^{166}Ho*, and* ^{192}Ir, **H.D. Choi**, Department of Nuclear Engineering, Seoul National University, Korea
9. *EMPIRE calculations of nuclear reaction cross sections for production of therapeutic radionuclides*, **R. Capote**, *IAEA, Nuclear Data Section, Vienna, Austria.*

Tuesday, 30 May

09:00 - 12:30 **Session 2: Discussions on key topics**

[Coffee break as appropriate]
Established Therapeutical Radioisotopes:
Review of actions and present status, outputs.

12:30 - 14:00 **Lunch**

14:00 – 18:00 **Session 2: Discussions on key topics (cont.)**

[Coffee break as appropriate]
Established Therapeutical Radioisotopes:
Review of actions and present status, outputs.

19:30 **Dinner at Restaurant in old city of Vienna**

Wednesday, 31 May

09:00 - 12:30 **Session 2: Discussions on key topics**

[Coffee break as appropriate]
Emerging Therapeutical Radioisotopes:
Review of actions and present status, outputs.

12:30 - 14:00 **Lunch**

14:00 – 18:00 **Session 2: Discussions on key topics (cont.)**

[Coffee break as appropriate]
Emerging Therapeutical Radioisotopes:
Review of actions and present status, outputs.

Thursday, 1 June

09:00 - 11:00 **Session 2: Discussions on key topics**

[Coffee break as appropriate]
Review of the decay data.
ENDF-6 formatting of the evaluations.
Review of the validations.

11:00 - 12:30 **Session 2: Discussions on key topics**

12:30 - 14:00 **Lunch**

14:00 – 18:00 **Session 3: Decisions and conclusions**

[Coffee break as appropriate]
Technical Series Report: Review of the structure and deadlines
Web page update (http://www-nds.iaea.org/radionuclides/)
Drafting of the meeting report

Friday, 2 June

09:00 - 18:00 Concluding Session

[Lunch and Coffee break intervals as appropriate]
Drafting of the meeting report (cont.)
Discussion and approval of the meeting report.
Final recommendations

International Atomic Energy Agency
Third Research Co-ordination Meeting on

"Nuclear Data for Production of Therapeutic Radionuclides"

IAEA Headquarters, Vienna, Austria
29 May to 2 June 2006
Conference Room A2774

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