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Nuclear Data for Production of Therapeutic Radionuclides

Summary Report of Second Research Coordination Meeting

IAEA Headquarters
Vienna, Austria
15-19 November 2004

Prepared by

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November 2004

IAEA NUCLEAR DATA SECTION, WAGRAMER STRASSE 5, A-1400 VIENNA

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Abstract

A summary is given of the Second Research Coordination Meeting on Nuclear Data for Production of Therapeutic Radionuclides. The new library of evaluated cross section will cover the reactor and/or accelerator production of therapeutic radionuclides to appropriate specific activities and purity along with the relevant decay data. Technical discussions and the resulting work plan of the Coordinated Research Programme are summarized for every reaction path to be evaluated, along with actions and deadlines. Participants' contributions to the RCM are also attached.

November 2004

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SUMMARY OF THE MEETING

The Second Research Coordination Meeting (RCM) on Nuclear Data for the Production of Therapeutic Radionuclides was held at the IAEA Headquarters in Vienna, Austria, from 15 - 19 November 2004. Primary aims of this meeting were to review the work done during the first two years of the CRP, discuss scientific and technical matters related to the subject, coordinate related tasks, expand the scope of the CRP to cover a few new reactions of interest and to assess assigned responsibilities.

Eight CRP participants and two external observers attended the Second RCM. 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. Trkov (Deputy Head, Nuclear Data Section) and R. Capote, who served as Scientific Secretary. The approved Agenda is attached (Appendix 1), as well as a list of participants and their affiliations (Appendix 2). Contributions to the meeting by CRP participants are included in Appendix 3.

A. Trkov (Deputy Head, IAEA Nuclear Data Section) 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 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 safe and efficient medical applications.

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

- Therapeutic radioisotopes that have established clinical uses (Appendix 3, Table 1) - ***Established Radioisotopes***.
- Less-commonly used but potentially interesting radioisotopes for which medical applications have been demonstrated (Appendix 3, Table 2) - ***Emerging Radioisotopes***.

Experimental data compilations and selection and preliminary 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	$^{31}\text{P}(n,\gamma)$	Choi	R

*R = Reactor, A = Accelerator

JENDL-3.3 file seems to be the best at low and intermediate energies. At thermal energies all the data libraries agree 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 the systematics (0.433 mb). Structures in JENDL-3.3 over the high-energy region are derived from inelastic levels. The junction of the resolved and unresolved resonance regions looks bad for ENDF/B-VI file. Therefore, JENDL-3.3 is recommended up to 1 MeV, and ENDF/B-VI above 1 MeV.

^{32}P	$^{32}\text{S}(n,p)$	Qaim	R,A
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Although the $^{32}\text{S}(n,p)$ reaction is in IRDF-90, further studies are required to address discrepant data in the plateau region. The JENDL dosimetry file seems to be the best evaluation, but according to BME-NTI-251/2001 (September 2001) there is a lack of consistency between File 3 (lower-energy limit 0.92 MeV) and File 33 (lower-energy limit 1.5 MeV, page 14); although there is a newer evaluation, data in File 33 were taken from the superseded IRDF-85 dosimetry file (page 19). Shibata should be contacted. Spectrum-averaged measurements are available: A. Calamand "Cross sections for fission neutron spectrum induced reactions", *Handbook on Nuclear Activation Cross Sections*. Technical Report Series No. 156, IAEA Vienna (1974) p. 273; for an updated version compare with JEF Report 14, OECD-NEA, Paris, France (1994). The structure in the cross section just above threshold cannot be obtained by any model calculation. ENDF/B-VI or JENDL/D-99 evaluations can be chosen. Only experimental data should appear in the diagram. Qaim should look at the experimental data and the new IRDF-2002, and send the diagram to Sublet.

^{89}Sr	$^{89}\text{Y}(n,p)$	Qaim	R,A
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^{89}Sr is an important pure beta emitter, produced in large amounts for medical applications. Dmitrovgrad (Russia) high flux reactor uses this reaction pathway with success. New ^{89}Y experimental data from Julich exist in the energy region 6-12 MeV; Qaim will send them to Capote for insertion into EXFOR. Capote will do the evaluated data selection including the latest LANL and BRC evaluations. The data should be sent to Sublet.

^{89}Sr	$^{88}\text{Sr}(n,\gamma)$	Betak	R
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In the different evaluated files there is a consistent agreement in the thermal energy region but different resonance structures. JENDL-3.3 is in better agreement with measurements. High energy JENDL-3.3 is acceptable, but Betak has some doubts in the high-energy range, where direct capture effects should be investigated. Choi to send the data file to Betak for improvement in the high-energy region.

^{90}Y	$^{235}\text{U}(n,f) \text{ } ^{90}\text{Sr} \rightarrow ^{90}\text{Y}$ generator	Sublet	R
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This is the actual route of production of very commonly used ^{90}Y isotope. The cumulative and independent yields have been analysed. The yield of ^{89}Sr needs to be provided as well, because of 50-days half-life and presence as impurity in the stock. Literature search will be performed to find possible existing measurements for nuclides other than ^{235}U .

^{90}Y	$^{89}\text{Y}(n,\gamma)$	Carlson	R
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A difficult reaction for which Sublet sent LANL and BRC data to IAEA for further analysis. Direct capture effect measurements exist. JEFF-3.0/A and TNG evaluations look better. Sublet and Carlson need to consult on the resonance range and resonance integral.

^{90}Y	$^{90}\text{Zr}(n,p)$	Carlson	R
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Carlson shows evaluated data comparison with new Geel experimental data for the metastable state. The (n,np + pn + d) channels need to be considered at energies beyond 10 MeV. Qaim will send experimental data to Carlson.

^{103}Pd	$^{102}\text{Pd}(n,\gamma)$	Carlson	R
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This could be an important production route for this commonly used radioisotope, if highly enriched target material is used. The evaluated data are based on model calculations only. A Single Resonance Approximation method was used for JEFF-3.0/A, with good thermal cross sections agreement with Mughabghab for ENDF/B-VI. ENDF-B-VI thermal data seems better (Wescott g-factor); JEFF-3.0/A SRA is to be renormalized to the experimental Resonance Integral measurement of 10.0 +/- 2.0 barns.

^{103}Pd could be produced as well by $^{104}\text{Pd}(\gamma,n)$ reaction. An evaluation from KAERI http://www-nds.iaea.org/photonuclear/recommended/pd104_kaeri.dat exists and could be considered.

^{103}Pd	$^{103}\text{Rh}(p,n)$	Qaim, Shubin	A
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Several measurements exist, a choice has been made, and the file can be finished. Minor problem with one very weak gamma emission probability remains. Neutron counting and activation techniques have been used. The data should be in EXFOR. STAPRE calculation has been used as a profile guideline to select a set of measurement points (neutron and X-ray only, the gamma measurements have been discarded). The cross section has been evaluated and can be adopted now or with minor correction in the peak. A Pade or cubic-spline fitting needs to be done. For impurity consideration the (p,pn) channel which leads to two ^{102}Rh isomers (2.9 years and 207 days) has been measured as well, and should be evaluated.

At least 20 cyclotrons have been recently built in the USA, which make use of this production route.

^{103}Pd	$^{103}\text{Rh}(d,2n)$	Tarkanyi, Shubin	A
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Only one experimental data set; however, X and gamma measurements do not give the same answer. Sets of X-ray data are preferred and need to be fitted. Thick target yield measurements exist as well. With deuteron projectile, the yield is twice the proton yield. The (d,p2n) reaction needs to be evaluated as an impurity route - leads to two isomers that need to be considered.

^{125}I	$^{124}\text{Xe}(n,\gamma)^{125}\text{Xe} \rightarrow ^{125}\text{I}$	Betak	R
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Two most important iodine isotopes produced by reactors are ^{125}I and ^{131}I . Good agreement between libraries, although only JEFF-3.0/A contains a direct capture component. One resonance integral measurement has been made that gives 3600 +/- 700 b. The study needs to be extended to the capture cross section of ^{125}I . High-energy model calculation will be performed.

^{131}I	$^{130}\text{Te}(n,\gamma)^{131}\text{Te} \rightarrow ^{131}\text{I}$	Choi	R
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Two channels exist and the metastable need to be considered. No evaluations seem to fit the low resonance range. The EXFOR Obninsk 1968 Dovbenko 40006003 entry data given in barn should be in millibarn. Analysis will continue.

^{131}I	$^{235}\text{U}(n,f)$	Sublet	R
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This is one of the most important therapeutic radioisotopes produced and used worldwide, and is an extremely well known fission element for which the yield should have been measured, and will be reported.

^{137}Cs	$^{235}\text{U}(n,f)$	Sublet	R
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^{137}Cs (gamma and beta emitter) is used in brachytherapy. This is an extremely well known fission element, for which the yield should have been measured, and will be reported.

153Sm	$^{152}\text{Sm}(n,\gamma)$	Betak	R
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Significant emphasis is being placed on this radionuclide for medical applications. 22612005 and 68005005 EXFOR entries data are in barns but should be millibarns. Preequilibrium contribution should be added to the high energy EMPIRE calculation. ENDF/B-VI or JENDL-3.3 can be adopted up to the end of the unresolved resonance range. Their resonance parameter MF-2 files are equivalent. Carlson to send data to Betak.

^{186}Re	$^{185}\text{Re}(n,\gamma)$	Sublet	R
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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. The final evaluation can be

undertaken.

^{186}Re	$^{186}\text{W}(p,n)$	Tarkanyi, Shubin	A
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Significant emphasis has been placed on this radionuclide for various medical applications. Three old experimental data sets exist, but some corrections are needed on one of them. The selected experimental data will be fitted. The experimental peak appears to be too narrow. Model calculations, including isomer production, will be performed by Capote.

^{186}Re	$^{186}\text{W}(d,2n)$	Tarkanyi, Shubin	A
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Five experimental data sets exist. A selection has been made and the data fitting will be completed. Model calculations, including isomer production, will be performed by Capote.

^{188}Re	$^{186}\text{W}(n,\gamma)\rightarrow^{187}\text{W}(n,\gamma)^{188}\text{W}\rightarrow$ $\rightarrow^{188}\text{Re}$ generator	Sublet	R
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One integral Oak Ridge measurement on the ^{187}W exists; Qaim will provide the reference to Sublet. The first capture reaction has already been validated by both differential and integral measurements. The second one will be based on theoretical model calculations, with only one resonance integral experimental value to be used.

^{188}Re	$^{187}\text{Re}(n,\gamma)$	Carlson	R
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ENDF/B-VI contains covariance data and could be chosen. Good agreement with differential measurements, thermal cross section and resonance integral.

^{192}Ir	$^{191}\text{Ir}(n,\gamma)$	Choi	R
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ENDF/B-VI and NGATLAS data exist. Three isomeric states co-exist and need to be analysed. More extensive analysis needs to be undertaken and reported.

^{192}Ir	$^{192}\text{Os}(p,n)^{192}\text{Ir}$	Qaim, Shubin	A
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Action on Julich group to measure this excitation function. The enriched material was bought and the measurements completed. Nuclear model calculations for all isomers using the EMPIRE code have been done, and agree well with the experimental data. Data fitting will be carried out in the usual way.

^{192}Ir	$^{192}\text{Os}(d,2n)^{192}\text{Ir}$	Qaim, Tarkanyi	A
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A newly added reaction for which no data exist in the literature. New measurements should be performed. Data fitting will be done in the usual manner, along side model calculations.

Emerging Radionuclides

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

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

One of the most important emerging therapeutic radionuclides that permits a combination of therapy and positron emission tomography. The decay data need to be changed to 38% β^- , 17.4% β^+ and 44.6% electron capture. A cleanup of an actual evaluated file is necessary to make a formal proposal. The decay data need to be reviewed, in particular the intensity of the weak 1346-keV gamma line.

^{64}Cu	$^{64}\text{Ni}(p,n)$	Qaim, Shubin	A
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This pathway is extensively used in the National Institute of Health (Bethesda USA) and in Saint Louis (Missouri USA). However, this route of production is only in the planning stage in the European Union (Italy), although the method was first suggested by the Julich group. Several experimental data sets are available, but two of them are not in EXFOR. The reaction threshold is at 2.5 MeV. The EXFOR data set (A0112) of Nemashkalo 83 is incorrectly expressed as microbarns instead of millibarns. Experimental data selection has been made; Levkovskii set appears too high. ALICE-IPPE model calculations have been made.

^{64}Cu	$^{64}\text{Ni}(d,2n)$	Nortier	A
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One set of experimental data is available (Zweit et al. 1991). Thick target yield calculations need to be used to validate the cross section data. The excitation function looks good, with a peak height at 800 mb. There is some uncertainty between target yield and cross section, and a literature search will be performed. Comparisons of nuclear model calculation profiles are needed with ALICE or EMPIRE codes.

Action: thick target yield measurement (Qaim, Scholten, Tarkanyi) will be performed if suitable target samples are available.

^{64}Cu	Zn(d,x)	Nortier, Shubin	A
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Potentially an important reaction, a literature search has to be done and new experimental data identified. Zn(d, α) ^{64}Cu experimental data exist, but are rather old (1963 Williams); new data sets from Milan and Debrecen have been produced over a wider energy range and from Julich (up to 14 MeV) on natural Zn. However, data selection needs to be done, keeping in mind that one group used 511-keV annihilation radiation while the other adopted the weak gamma line at 1346-keV mentioned above.

Need to check if this reaction is of any value above 25 MeV because of the formation of ^{67}Cu as impurity. Highly-enriched $^{66}\text{Zn}(d,\alpha)$, chemically separated experimental data sets exist from Julich, and can be used to evaluate the natural data up to 14 MeV.

^{64}Cu	$^{64}\text{Zn}(n,p)$	Choi	R
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Sublet to send the excitation curve to Choi and the IAEA (www-nds.iaea.org/radionuclides/). Spectrum-averaged values to be calculated by INTER and compared with integral experimental data.

^{67}Cu	$^{67}\text{Zn}(n,p)$	Choi	R
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Sublet to send the excitation curve to Choi. Spectrum-averaged values to be calculated by INTER and compared with integral experimental data. An unaccounted Julich data set exists, which is not in EXFOR. Qaim to send data to Sublet.

^{67}Cu	$^{68}\text{Zn}(p,2p)$	Nortier, Shubin	A
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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%) and data fitting can start. Production of ^{64}Cu as impurity via $^{68}\text{Zn}(p,\alpha n)$ and $^{68}\text{Zn}(p,2p3n)$ reactions need to be considered. EMPIRE (p,2p) calculation is also required. Theoretical calculation seems to indicate that the contribution of the neutron reactions $^{68}\text{Zn}(n,d) + ^{68}\text{Zn}(n,np)$ can be important in the case of a thick target, and this needs to be considered as well. Sublet can calculate reaction rates if neutron spectra (Capote) are provided along with cross section excitation function.

^{67}Cu	$^{70}\text{Zn}(p,\alpha)$	Qaim, Shubin	A
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Two experimental data sets exist up to 30 MeV, one from Julich and another from Levkovskii (not yet adjusted, 0.80) on $^{70}\text{Zn}(p,x) ^{67}\text{Cu}$. Chemical separation is mandatory, especially if the enrichment of ^{70}Zn is not very high because of ^{67}Ga production. Some de-selection of the experimental data points is necessary. An ALICE-IPPE model calculation has been performed and fits the experimental data well.

^{67}Ga	$^{68}\text{Zn}(p,2n), ^{67}\text{Zn}(p,n)$	Capote	A
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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. It has already been previously evaluated for diagnostic purpose (earlier CRP).

^{86}Y	$^{86}\text{Sr}(p,n)$	Qaim, Shubin	A
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A new reaction added to the list: importance of positron emitting ^{86}Y is increasing for quantification of dosimetry, while using the purely β^- emitting radionuclide ^{90}Y for therapy. Data fitting will be done.

^{105}Rh	$^{104}\text{Ru}(n,\gamma)^{105}\text{Ru} \rightarrow ^{105}\text{Rh}$	Choi	R
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A new reaction added to the list: this transition metal, β^- emitting radioisotope is of great interest and potential.

^{111}In	$^{111}\text{Cd}(p,n), ^{112}\text{Cd}(p,2n)$	Capote	A
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This radionuclide has been in use as a diagnostic SPECT nuclide for some time. However, since it is an almost pure Auger electron emitter and has a favourable half-life of 2.8 days, ^{111}In is also finding increasing use in metabolic therapy. Has already been previously evaluated for diagnostic purpose (earlier CRP).

$^{114\text{m}}\text{In}$	$^{114}\text{Cd}(p,n)$	Tarkanyi, Shubin	A
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Action on Debrecen group to measure this excitation function. The enriched material has been bought and the measurements completed. New measurements on natural targets have also been carried out and data evaluation has been completed. Data fitting needs to be undertaken.

$^{114\text{m}}\text{In}$	$^{116}\text{Cd}(p,3n)$	Tarkanyi, Shubin	A
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This reaction could be of interest at cyclotrons with energies around 30 MeV, especially using an enriched thin target at a low glancing angle. The excitation function of this reaction was measured at Debrecen and Cape Town using natural cadmium, with the correction for the (p,n) contribution using the data measured on enriched ^{114}Cd . Data fitting needs to be undertaken.

$^{114\text{m}}\text{In}$	$^{114}\text{Cd}(d,2n)$	Tarkanyi, Shubin	A
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Action on Debrecen group to measure this excitation function. The enriched material has been bought and the measurements completed. New measurements on natural targets have also been carried out. Natural and enriched target measurements have been performed, and two other existing sets were discarded. Fitting and EMPIRE model calculations need to be performed.

^{124}I	$^{124}\text{Te}(p,n)$	Qaim, Tarkanyi	A
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One of the most important emerging therapeutic radionuclides that allows a combination of therapy and positron emission tomography. This reaction is the best method to produce ^{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: new ratio is 0.22 +/- 1%.

^{124}I	$^{124}\text{Te}(d,2n)$	Nortier, Shubin	A
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Two sets of experimental data exist from Julich and Brookhaven. Original Brookhaven cross-section data are wrong, and were re-calculated from the reported thin target yield values. This information needs to be passed on to EXFOR as well. Both sets look good and can be used for data fitting. Because of the ^{125}I impurity, the $^{124}\text{Te}(d,n)$ reaction needs to be considered as well.

^{124}I	$^{125}\text{Te}(p,2n)$	Nortier, Shubin	A
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Only one data set was recently measured (2001) and is available: certainly performed on an enriched target. Comparison must be made of reported thick target yields data with predictions from the excitation function. $^{125}\text{Te}(p,2n)$ reaction seems to be the best from a yield point of view, but the ^{125}I impurity needs to be considered.

^{149}Pm	$^{148}\text{Nd}(n,\gamma)^{149}\text{Nd} \rightarrow ^{149}\text{Pm}$	Carlson	R
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A new reaction added to the list: this rare earth isotope, β^- emitting is of great interest.

^{166}Ho	$^{165}\text{Ho}(n,\gamma)$	Betak	R
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Two evaluated files (ENDF/B-VI and JEF-2.2) are in good agreement in the low-energy region, but significant differences occur in the high-energy range. An isomeric state exists, and needs to be accounted for. Some existing EXFOR entries need to be re-normalised.

^{166}Ho	$^{164}\text{Dy}(n,\gamma) \rightarrow ^{165}\text{Dy}(n,\gamma) \rightarrow$ $\rightarrow ^{166}\text{Dy} \rightarrow ^{166}\text{Ho}$	Sublet	R
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The existing evaluation needs to be analysed.

^{169}Yb	$^{168}\text{Yb}(n,\gamma)$	Sublet	R
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An Auger electron emitter that is gaining interest. The total cross section looks good, but the branching ratio needs to be corrected.

^{169}Yb	$^{169}\text{Tm}(p,n)$	Qaim, Shubin	A
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Action on Julich group to measure this excitation function. The measurements have been completed in 2004 as collaboration between Julich and Debrecen. The measurements at different cyclotrons agree, and data analysis is in progress.

^{177}Lu	$^{176}\text{Yb}(n,\gamma)^{177}\text{Yb} \rightarrow ^{177}\text{Lu}$	Sublet	R
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This β^- emitting radioisotope is used in palliative therapy via interstitial implantation as a liquid gel injection. This isotope is mainly produced in France for Europe, and in Missouri

for the USA. The existing data have been assessed, but more work is needed particularly on the branching ratio.

^{177}Lu	$^{176}\text{Lu}(n,\gamma)$	Sublet	R
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The existing data have been assessed and an evaluation selected for both states.

^{211}At	$^{209}\text{Bi}(\alpha,2n)$	Tarkanyi, Shubin	A
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A significant amount of interest exists in this alpha emitting radionuclide. Compilation of experimental data has been analysed alongside new measurements from Debrecen, and exceptional agreement occurs. ALICE-IPPE model calculation has been undertaken, showing a small energy shift. $^{209}\text{Bi}(\alpha,x)^{210}\text{Po}$ cumulative and $^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$ reactions have been measured as well, showing some discrepancy above 40 MeV. EMPIRE code model calculations are also available, showing good agreement. Data fitting can commence for the production of ^{211}At and impurity ^{210}At .

^{213}Bi	decay of ^{225}Ac	Carlson	D
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This important nuclide exists in nuclear waste from the ^{233}U cycle, and can be chemically recovered (usefully extracted from waste streams). Three alpha decay processes (100%, 99.99% and 99.98%) occur. MIRD and ENDF files exist. Help of an IAEA expert on decay data may be required.

^{225}Ac	$^{226}\text{Ra}(p,2n)$	Menapace, Capote	A
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This is a difficult reaction to measure. Only one set of experimental data from Karlsruhe-Ispra (Morgenstern, Apostolidis) is available. An ALICE-IPPE model calculation has been performed, with a peak of 450 mb at around 16 MeV. EMPIRE model calculation peaks at 600 mb at the same energy. The above preliminary experimental data tend to support the EMPIRE model calculation.

^{225}Ac	Decay of $^{233}\text{U} \rightarrow ^{229}\text{Th}$	Carlson	R,D
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This radionuclide occurs in the ^{233}U fuel cycle. MIRD and ENDF files exist. ND-2004 Santa Fe abstract "Reactor production of Th-229", by Mirzadeh (Oak Ridge) points out that one needs a high flux reactor. More work needs to be done.

COMMENTS AND RECOMMENDATIONS

Extensive work needs to be done in the next 12 to 15 months so that the necessary progress can be achieved before the next and last meeting. References to missing EXFOR data also need to be reported to the IAEA Nuclear Data Section (to Technical Officer and O. Schwerer).

Transmission of data

Neutron data

All final neutron results and files will be transmitted when ready to Sublet, who will then send the ENDF-6 formatted file to the IAEA Nuclear Data Section.

Calculations of neutron-induced reactions:

- for Maxwellian spectrum, average with $T = 300\text{K}$ and integration limits $1.E-05$ to 10 eV ;
- for resonance integrals, use $1/E$ spectrum with limits of 0.55 eV to 2 MeV ;
- for fission neutron spectrum, average a Maxwellian fission spectrum with effective temperature $T = 1.35\text{ MeV}$, and integration limits from 1 keV to 20 MeV .

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, who will collate and forward them to Shubin for fitting purposes. Shubin 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 evaluated curves and calculated yields. Tarkanyi will also send the data to Capote and Menapace for record and model calculations.

NDS staff 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 file format will be ENDF-6.

Uncertainties

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

For charged-particle reactions, the uncertainty estimation of the fitted curve will be discussed at the next meeting on the basis of the recommendations of each evaluator. NDS staff will format in the proper way.

Validation

Neutron data validation can be carried out with what is 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 will be performed using the d-Be source in Julich.

Charged-particle data validation requires well-defined experiments on integral yield measurements. Natural targets can also be used for data validation. Existing experimental

thick target yields should be critically analysed and used if considered reliable. Part of the experimental integral validation of the (p,n), (p,2n) and (d,2n) reactions of this CRP will be performed at Debrecen and Julich.

Action: Capote will update the dedicated Web site (www-nds.iaea.org/radionuclides/) with online data and report access (Deadline Jan. 2005).

Expected Outputs of CRP

A few more reactions were 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,
- TECDOC report,
- IAEA-NDS Worldwide Web online access to database.

Timescale

Third and final meeting will be held sometime in March-May 2006. By that time, participants are expected to provide:

- all of their evaluated data, as agreed
- contributions to TECDOC in electronic draft form.

Additional points of note

The next meeting could be held in Brazil.

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

- Spring meeting of the ACS, partly organized by LANL,
- Neutron in Nuclear Physics Application & Technology, Pavia, September 2005,
- NEMEA-3, Bulgaria, September 2005,
- IRRMA-6, Hamilton, Canada, June 2005,
- ICI-5 International Conference on Isotopes, Brussels, April 2005,
- Asian-Pacific Chemical Societies, Radiochemistry conference, Beijing, October 2005.

AGENDA

International Atomic Energy Agency

Second Research Coordination Meeting on

“Nuclear Data for Production of Therapeutic Radionuclides”

IAEA Headquarters, Vienna, Austria

15 - 19 November 2004

Meeting Room A0418

Monday, 15 November

08:30 - 09:20 Registration (IAEA Registration desk, Gate 1)

09:30 - 10:30 Administrative and Financial Matters related to participants
Coffee break

10:30 - 11:00 Opening Session

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

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 the Production of Emerging Therapeutic Radionuclides*, **J-Ch. Sublet**, CEA, France.
5. *New evaluations of (n,p) reaction cross sections on ^{32}S , ^{89}Y and ^{90}Zr and calculations of charged particles induced reaction cross sections for $^{186}\text{W}(p, n)^{186}\text{Re}$, $^{186}\text{W}(d, 2n)^{186}\text{Re}$ and $^{226}\text{Ra}(p, 2n)^{225}\text{Ac}$* , **Y. N. Shubin**, 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. Běťák**, 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. **E. Menapace**, *ENEA, Division for Advanced Physical Technologies, Italy.*

Evaluated data retrieval and comparison with experimental EXFOR data (ENDVER package), **A. Trkov**, IAEA, Nuclear Data Section, Vienna, Austria.

17:30 Reception –

Tuesday, 16 November

09:00 - 12:30 Session 2: Discussions on key topics
[Coffee break as appropriate]

Established Therapeutical Radioisotopes:
Review of actions, present status, future actions, 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, present status, future actions, outputs.

Wednesday, 17 November

09:00 - 12:30 Session 2: Discussions on key topics
[Coffee break as appropriate]

Emerging Therapeutical Radioisotopes:
Review of actions, present status, future actions, 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, present status, future actions, outputs.

Thursday, 18 November

09:00 - 11:00 Session 2: Discussions on key topics
[Coffee break as appropriate]

Decay data requirements.
ENDF-6 formatting of the evaluations.
Validation of the evaluations

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

New nuclear data requirements for medical applications.
Additional reactions to be included in the evaluation procedure.

12:30 - 14:00 Lunch

14:00 – 18:00 Session 3: Decisions and conclusions
[Coffee break as appropriate]

TECDOC: Review of the structure and deadlines
Web page update (<http://www-nds.iaea.org/radionuclides/>)
Drafting of the meeting report

Friday, 19 November

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. Next RCM.

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Table 1. Established Therapeutic Radioisotopes

Radionuclide	T _{1/2}	E _{max} in MeV	Production route	R/A/D *
³² P	14.3 d	1.7 β ⁻	³¹ P(n, γ)	R
			³² S(n, p)	R,A
⁸⁹ Sr	50.5 d	1.5 β ⁻	⁸⁹ Y(n, p)	R,A
			⁸⁸ Sr(n, γ)	R
⁹⁰ Y	2.7 d	2.3 β ⁻	⁹⁰ Zr(n, p)	R,A
			⁸⁹ Y(n, γ)	R
			²³⁵ U(n, f) FP ⁹⁰ Sr → ⁹⁰ Y generator	R
¹⁰³ Pd	17.0 d	Auger electrons, x-rays	¹⁰² Pd(n, γ)	R
			¹⁰³ Rh(p, n)	A
			¹⁰³ Rh(d, 2n)	A
			¹⁰⁴ Pd(γ,n)	A
¹²⁵ I	60.0 d	Auger electrons	¹²⁴ Xe(n,γ) ¹²⁵ Xe → ¹²⁵ I generator	R
¹³¹ I	8.0 d	0.6 β ⁻	¹³⁰ Te(n, γ) → ¹³¹ Te → ¹³¹ I	R
			²³⁵ U(n, f) FP	R
¹³⁷ Cs	30.97 y	0.5 β ⁻	²³⁵ U(n, f) FP	R
¹⁵³ Sm	1.9 d	0.8 β ⁻	¹⁵² Sm(n, γ)	R
¹⁸⁶ Re	17.0 h	1.1 β ⁻	¹⁸⁵ Re(n, γ)	R
			¹⁸⁶ W(p, n)	A
			¹⁸⁶ W(d, 2n)	A
¹⁸⁸ Re	17.0 h	2.0 β ⁻	¹⁸⁶ W(n, γ) → ¹⁸⁷ W(n, γ) ¹⁸⁸ W → ¹⁸⁸ Re generator	R
			¹⁸⁷ Re(n, γ)	R
¹⁹² Ir	73.8 d	0.7 β ⁻	¹⁹¹ Ir(n, γ)	R
			¹⁹² Os(p, n) ¹⁹² Ir	A
			¹⁹² Os(d, 2n) ¹⁹² Ir	A

*R = Reactor, A = Accelerator, D = Decay; reactors are usually used for (n, p) reactions, but accelerator production would also be possible if the neutron production is sufficiently intense.

Table 2. Emerging Therapeutic Radioisotopes.

Radionuclide	T _{1/2}	E _{max} in MeV	Production route	R/A/Decay *
⁶⁴ Cu	12.7 h	0.6 β ⁻ 0.7 β ⁺	⁶³ Cu(n, γ)	R
			⁶⁴ Ni(p, n)	A
			⁶⁴ Ni(d, 2n)	A
			⁶⁴ Zn(n, p)	R
			⁶⁴ Zn(d, x)	A
⁶⁷ Cu	2.6 d	0.6 β ⁻	⁶⁷ Zn(n, p)	R
			⁶⁸ Zn(p, 2p)	A
			⁷⁰ Zn(p, α)	A
⁶⁷ Ga	3.2 d	Auger electrons	⁶⁸ Zn(p, 2n)	A
			⁶⁷ Zn(p, n)	A
⁸⁶ Y	14.74 h	β ⁺	⁸⁶ Sr(p, n)	A
¹⁰⁵ Rh	35.4 h	β ⁻	¹⁰⁴ Ru(n, γ) ¹⁰⁵ Ru → ¹⁰⁵ Rh	R
¹¹¹ In	2.8 d	Auger electrons	¹¹¹ Cd (p, n)	A
			¹¹¹ Cd(p, 2n)	A
^{114m} In	2.8 d	Auger electrons	¹¹⁴ Cd (p, n)	A
			¹¹⁴ Cd(d, 2n)	A
			¹¹⁶ Cd(p, 3n)	A
¹²⁴ I	4.2 d	2.1 β ⁺	¹²⁴ Te(p, n)	A
			¹²⁴ Te(d, 2n)	A
			¹²⁵ Te(p, 2n)	A
¹⁴⁹ Pm	2.12 d	β ⁻	¹⁴⁸ Nd(n, γ) ¹⁴⁹ Nd → ¹⁴⁹ Pm	R
¹⁶⁶ Ho	26.8 h	1.9 β ⁻	¹⁶⁵ Ho(n, γ)	R
			¹⁶⁴ Dy(n, γ) → ¹⁶⁵ Dy(n, γ) → ¹⁶⁶ Dy → ¹⁶⁶ Ho	R
¹⁶⁹ Yb	32.0 d	Auger electrons	¹⁶⁸ Yb(n, γ)	R
			¹⁶⁹ Tm(p, n)	A
¹⁷⁷ Lu	6.7 d	0.5 β ⁻	¹⁷⁶ Lu(n, γ)	R
			¹⁷⁶ Yb(n, γ) ¹⁷⁷ Yb → ¹⁷⁷ Lu	R
²¹¹ At	7.2 h	5.9 α	²⁰⁹ Bi(α, 2n)	A
²¹³ Bi	45.6 m	8.4 α	Decay of ²²⁵ Ac	D
²²⁵ Ac	10.0 d	5.8 α	²²⁶ Ra(p, 2n)	A
			decay of ²³³ U → ²²⁹ Th	R,D

SUMMARY OF THE PRESENTATIONS BY PARTICIPANTS

- 4.1. Bětak, Emil, Progress Report on IAEA Research Contract No.12425, “Possible production of selected therapeutic radioisotopes of $A > 80$ using the (n,γ) reactions with fast neutrons”
- 4.2. Carlson, Brett, Progress Report on IAEA Research Contract No. 12418, “Production cross sections and decay properties of several radionuclides with therapeutic applications”
- 4.3. Choi, Hee Dong, Progress Report on IAEA Research Contract No. 12489, “Neutron (n,γ) cross section and decay data for P-32, Sr-89, I-131, Ho-166 and Ir-192”
- 4.4. Nortier, Francois M., Progress Report on IAEA Research Agreement No. 12490, “Experimental nuclear data evaluations by the LANL group”
- 4.5. Qaim, Syed M., Progress Report on IAEA Research Agreement No. 12488, “Measurement and standardisation of nuclear reaction cross section data for production of some therapeutic radionuclides”
- 4.6. Shubin, Yuri N., Progress Report on IAEA Research Contract No. 12420, “Calculation and evaluation of nuclear reaction cross sections for the production of therapeutic radionuclides”
- 4.7. Sublet, Jean-Christophe, Progress Report on IAEA Research Agreement No. 12487, “Review of selected cross-sections and fission yields for the production of emerging therapeutic radionuclides”
- 4.8. Tarkanyi, Ferenc T., Progress Report on IAEA Research Contract No. 12419, “Experiments and data evaluations by the ATOMKI group”

**Progress Report on IAEA Research Contract No. 12425
Possible Production of Selected Therapeutic Radioisotopes of
A>80 Using the (n, γ) Reactions with Fast Neutrons**

E. Betak

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The main attention has been given to calculations of the (n, γ) reactions in the energy range 100 keV to 20 MeV, and their comparison to the data. The EMPIRE-II code (version 2.18 Mondovi) [1] has been employed to this aim, and the experimental data have been taken from the June version of EXFOR [2]. Though significant progress has been reported in literature in (n, γ) reactions, not much of these results can be applied directly to the selected isotopes. New information on the strength functions is available for Y-89, Te-124, Sm-150, Ho-165 and Ir-192i [3-5], what are the selected nuclei and/or the nuclei in their immediate vicinity; and Plujko presented study on the forms of the giant resonance and their influence on the gamma absorption and emission recently [6]. Production of therapeutic Ir-192 by another reaction, namely (p,n) (which is of course not a subject of this contract, but giving a useful information on other production way), has been given in [7].

The plan for the near future includes switch from version 2.18 to much more sophisticated 2.19 of the EMPIRE code [8] and the intercomparison between TALYS [9] and EMPIRE codes, which are both to be released in the nearest weeks.

In addition to the theoretical studies of production of therapeutic isotopes by means of the (n, γ) reactions we have also studied (mainly experimentally) possible ways of production of diagnostic isotope In-111 by neutrons [10,11] and also by protons [11]. Especially the latter reaction is capable to produce the purest in the world isotope of In-111.

Apart of this effort, but also of potential use for studies of production of medical isotopes is the generalization of the pre-equilibrium description of the cluster emission [12].

- [1] HERMAN, M.: EMPIRE-II statistical model code for nuclear reaction calculations (version 2.18 Mondovi), IAEA NDS (2002)
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- [3] VASILEVA, E.V., et al.: Yad. Fiz. 64 (2001), 195
- [4] VARLAMOV, V.V., et al.: in INDC(CCP)-440, p. 37, IAEA (2004)
- [5] VARLAMOV, V.V., et al.: Izv. AN, Ser. Fiz. 67 (2003), 656
- [6] PLUJKO, V.A., et al.: contribution to the ND2004 conference
- [7] HILGERS, K., et al.: contribution to the ND2004 conference
- [8] HERMAN, M., et al.: contribution to the ND2004 conference
- [9] KONING, A., et al.: contribution to the ND2004 conference
- [10] BETAK, E., et al.: submitted to Radiochim. Acta
- [11] BETAK, E., et al.: presentation at the NEMEA-2 Workshop
- [12] BETAK, E., et al.: contribution to the ND2004 conference

**Progress Report on IAEA Research Contract No. 12418
Production Cross Sections and Decay Properties of Several
Radionuclides with Therapeutic Applications**

B.V. Carlson¹, A.D. Caldeira² and F.B. Guimarães²

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Introduction

We have performed reaction model calculations of the ⁹⁰Y producing reactions, ⁸⁹Y(n,γ)⁹⁰Y and ⁹⁰Zr(n,p)⁹⁰Y, and the capture reactions ¹⁰²Pd(n,γ)¹⁰³Pd, ¹²⁴Xe(n,γ)¹²⁵Xe, ¹⁵²Sm(n,γ)¹⁵³Sm and ¹⁸⁷Re(n,γ)¹⁸⁸Re. These calculations were compared to the experimental data available in the EXFOR library¹ and with previous evaluations in the ENDF formatted libraries¹. We have also calculated unshielded spectrum averaged cross sections for the reactions above using the available ENDF formatted libraries.

In addition, we have performed a preliminary comparison of the information available in the MIRD and JEF2.2 decay data libraries for the decay of ⁹⁰Y, ¹⁰³Pd, ¹²⁵Xe, ¹²⁵I, ¹⁵³Sm and ¹⁸⁸Re and for the α-emitting decay chain ²²⁵Ac→²²¹Fr→²¹⁷At→²¹³Bi as well as the decay of ²¹³Bi.

Discussion of Reactions

Production of ⁹⁰Y through the ⁸⁹Y(n,γ)⁹⁰Y and ⁹⁰Zr(n,p)⁹⁰Y reactions

The radioisotope ⁹⁰Y has a $J^\pi=2^-$ ground state with a half-life of $T_{1/2}=64.1$ h that decays exclusively by β^- emission. It has an $J^\pi=7^+$ isomeric state at $E_x=0.682$ MeV with a half-life of $T_{1/2}=3.19$ hrs that decays almost exclusively to the ground state but possesses a small branching ratio of 1.8×10^{-5} for β^- emission.

The ENDF/B-VI, JENDL-3.3, JEF-3.0 and JEF-3.0/A evaluations have been compared with the relatively abundant experimental data available for the neutron capture reaction ⁸⁹Y(n,γ)⁹⁰Y. All evaluations are in agreement with the evaluated value of the thermal cross section², but tend to underestimate the evaluated value of the resonance integral². At high energies, our evaluation provides slightly better agreement with the direct/semi-direct peak.

The ENDF/B-VI, JENDL-3.3 and JEF-3.0 evaluations have been compared with the experimental data available for the reaction ⁹⁰Zr(n,p)⁹⁰Y. None provide agreement we consider satisfactory. We are currently trying to resolve the discrepancy between model calculations and the high-energy Bayhurst and Prestwood data³ by analyzing new data from Geel⁴ for the reaction ⁹⁰Zr(n,p)^{90m}Y.

Production of ¹⁰³Pd through the neutron capture reaction ¹⁰²Pd(n,γ)¹⁰³Pd

The radioisotope ¹⁰³Pd has a $J^\pi=5/2^+$ ground state with a half-life of $T_{1/2}=16.99$ d that decays exclusively by electron conversion.

The ENDF/B-VI, JENDL-3.3, JEF-3.0 AND JEF-3.0/A evaluations agree with the evaluated value of the thermal cross section – The only available data point, other than the parameters of a single resonance. The ENDF/B-VI evaluation agrees with the values given for the average thermal cross section and resonance integral while the other evaluations do not. However, the ENDF/B-VI does not take into account the one known resonance. The three

distinct evaluations furnish different values of the capture cross section above the resonance region. A review is recommended of the systematics obtained from the evaluation of neighboring nuclei for which more experimental data is available.

Production of ^{125}I through the neutron capture reaction $^{124}\text{Xe}(n,\gamma)^{125}\text{Xe}\rightarrow^{125}\text{I}$

The radioisotope ^{125}Xe has a $J^\pi=1/2^+$ ground state with a half-life of $T_{1/2}=16.9$ hrs that decays by β^+ emission/electron conversion. It has a short-lived $J^\pi=9/2^-$ isomeric state at $E_x=0.252$ MeV with a half-life of $T_{1/2}=56.9$ s that decays exclusively to the ground state.

The ENDF/B-VI, JENDL-3.3, JEF-3.0 and JEF-3.0/A evaluations agree with the evaluated value of the thermal cross section and with the average thermal cross section but tend to underestimate the resonance integral. The three distinct evaluations again furnish different values of the capture cross section above the resonance region. Again, a review of the systematics obtained from the evaluation of neighboring nuclei is recommended.

Production of ^{153}Sm through the neutron capture reaction $^{152}\text{Sm}(n,\gamma)^{153}\text{Sm}$

The radioisotope ^{153}Sm has a $J^\pi=3/2^+$ ground state with a half-life of $T_{1/2}=46.284$ h that decays exclusively by β^- emission.

The ENDF/B-VI, JENDL-3.3, JEF-3.0 and JEF-3.0/A evaluations agree with the evaluated value of the thermal cross section and with the average thermal cross section. The ENDF/B-VI and JEF-3.0 evaluations agree with the evaluated value of the resonance integral while the JENDL-3.3 evaluation underestimates it. Discrepancies between the evaluations above about 5 MeV must still be assessed.

Production of ^{188}Re through the neutron capture reaction $^{187}\text{Re}(n,\gamma)^{188}\text{Re}$

The radioisotope ^{188}Re has a $J^\pi=1^-$ ground state with a half-life of $T_{1/2}=17.005$ h. It decays exclusively by β^- . It has a short-lived $J^\pi=(6)^-$ isomeric state at $E_x=0.172$ MeV with a half-life of $T_{1/2}=18.6$ m that decays exclusively to the ground state.

The ENDF/B-VI, JEF-3.0 and JEF-3.0/A evaluations agree with the evaluated value of the thermal cross section, the average thermal cross section, the resonance integral and with the available experimental data above the resonance region. Due to its better agreement with the average cross sections, we recommend use of the ENDF/B-VI evaluation.

Decay Data

We have performed a preliminary comparison of the information available in the MIRD and JEF2.2 decay data libraries¹ for the decay of ^{90}Y , ^{103}Pd , ^{125}Xe , ^{125}I , ^{153}Sm and ^{188}Re and for the α -emitting decay chain $^{225}\text{Ac}\rightarrow^{221}\text{Fr}\rightarrow^{217}\text{At}\rightarrow^{213}\text{Bi}$ as well as the decay of ^{213}Bi . In general, the ENDF/B-VI formatted JEF2.2 decay files are fairly complete but show small discrepancies with the newer MIRD evaluations.

Further Work

In the coming year, we plan to:

- Complete the analysis of the reaction $^{90}\text{Zr}(n,p)^{90}\text{Y}$;
- Study the systematics of model calculations of neutron-induced reactions in nuclei neighboring ^{102}Pd and ^{124}Xe ;
- Study the mechanisms of capture reactions above 1 MeV (pre-equilibrium, direct/semi-direct mechanisms);
- Continue the verification of relevant decay data;

- Estimate uncertainties (covariances) of the evaluated cross sections.

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- [2] MUGHABGHAB, S.F., “Thermal neutron capture cross sections, resonance integrals and σ -factors”, INDC report, INDC(NDS)-440 (2003).
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Progress Report on IAEA Research Contract No. 12489
Neutron (n, γ) cross section and decay data for
P-32, Sr-89, I-131, Ho-166, and Ir-192

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1. ^{32}P production

$^{31}\text{P}(n,\gamma)^{32}\text{P}$ reaction cross sections were listed for production of P-32. Those data in BNL-325 [1], and in various libraries ENDF/B-VI, JEF-2, JENDL-3, BROND-2, CENDL-2 [2] are extracted while the experimental data are retrieved from EXFOR [3] by using ZVView [4]. For thermal neutron capture cross section, most libraries adopt experimental data. JENDL library considered the recent experimental data for thermal neutron capture cross section, while data for resonance region were calculated by using resonance parameters of Mughabghab [1]. ENDF evaluation, however, omits the resonance structure. Spectrum-averaged fast cross sections were generated by using INTER code [5] and they are relatively consistent. The JENDL library dataset is adopted by considering the consistency in the whole energy region under discussion.

2. ^{89}Sr production

Reaction cross sections of $^{88}\text{Sr}(n,\gamma)^{89}\text{Sr}$ were extracted from BNL-325, ENDF/B-VI, JEF-2, and JENDL-3. Dataset in JENDL library reflects best the experimental data of thermal neutron capture cross section, resonance measurement, and 1 MeV cross section. Cross sections in resonance region are obtained in JENDL library by using Mughabghab's parameters [1].

3. ^{131}I production

^{131}I is majorly produced by extraction from fission fragment which were generated after irradiation in reactor. This study, however, listed the reaction data for producing ^{131}I in the route of β^- decay of ^{131}Te which is produced by $^{130}\text{Te}(n,\gamma)$ reaction. ENDF and JEF libraries suggest similar values while the resonance and high energy region data in JENDL library are obtained by recalculation. Inconsistency in fast cross section results mainly from that around 10 MeV. JENDL data reproduce the average experimental data around 10 MeV.

4. ^{166}Ho production

Two libraries of ENDF and JEF exist for $^{165}\text{Ho}(n,\gamma)$ cross section. The JEF data were obtained by amended calculation in the high energy region while existing ENDF results were quoted in the other region. Resonance parameters were taken from BNL-325 [1]. Thermal capture cross sections and fission spectrum averaged cross sections are consistent.

5. ^{192}Ir production

In case of $^{191}\text{Ir}(n,\gamma)^{192}\text{Ir}$ cross section, only ENDF library suggests evaluation. The ENDF dataset covers, however, only high energy region above 10 keV. The experimental data are scarce through the whole energy region. The recent NGATLAS D/B [6] reports the cross section for the whole energy region. Both dataset disagree in the high energy region and hence detailed comparison is required.

6. Decay Data

Decay data are found in ENSDF, NuDat, MIRD, Table of Isotopes. Each database, however, is based on ENSDF data considering the editing purpose and application. Hence the decay data are mostly consistent in every database. This study compiled the data from MIRD [7] and RADLST [8]. The present lists extract the basic parameters including half-life, decay scheme, branching ratio, quantum energy from ENSDF library and decay β -spectrum could be calculated by using RADLST and RADAR. For fine energy step calculation of β -spectra, RADAR (RAAdiation Dose Assessment Resource) was used, which also provided with the information on dose assessment models and methods. RADLST calculates β - and bremsstrahlung spectra and also calculates the dose conversion factors. For each nuclide, decay scheme, decay data, and β -spectrum were plotted and tabulated. The decay data are based on MIRD and RADLST database.

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**Progress Report on IAEA Research Agreement No. 12490
Experimental Nuclear Data Evaluation by the LANL Group
LAUR-04-7732**

F. Meiring Nortier

Los Alamos National Laboratory

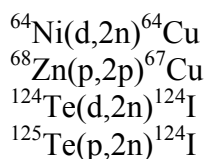
Current Operational Activities at LANL

The new Isotope Production Facility (IPF) at the Los Alamos National Laboratory facility uses a 100 MeV proton beam with beam currents of up to 250 μ A extracted from the existing LANSCE accelerator by means of a pulsed kicker magnet. The facility is used to irradiate a wide range of materials to produce a variety of radioisotopes of value to the DOE's Office of Isotopes for Medicine and Science including Sr-82, Ge-68, Cu-67, Na-22, Si-32, V-48, Zr-88, As-73, etc. Up to three targets can be irradiated simultaneously utilizing nominal production energy windows of 90-70 MeV, 65-45 MeV and 30-10 MeV. Cooling water flowing between the targets in the stack provides efficient cooling of the targets.

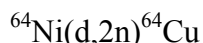
The first beam into new target station was achieved during December 2003. The new beam line, target station and a selection of high current targets were commissioned by the end of April 2004. Practical production schedules are designed to minimize overall production cost by maximizing the occupation of the three energy slots in such a way that a good mix of long- and short lived isotopes are made available on a regular basis. For this accurate and reliable excitation function data is needed in the energy range up to 100 MeV in order to develop optimized irradiation schedules. While experimental data for the production of some of the envisaged isotopes are available in the literature, accuracy is still lacking in many cases. For others no experimental data can be found and yield estimates have to be based solely on theoretical cross sections.

Cross Section Data Evaluation Activity

Four nuclear reactions involving accelerator-produced radioisotopes in the *emerging radioisotopes* category have been assigned to the LANL Group for evaluation. They are:

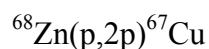


Experimental cross section data available in the literature have been compiled for all four the reactions and evaluations of the respective measurements were performed.

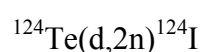


One set of cross section data is available^[1]. Cross sections for the $^{64}\text{Ni}(d,2n)^{64}\text{Cu}$ reaction were measured for deuterons incident on $^{\text{nat}}\text{Ni}$. The total errors in the cross section data are between 11% and 17%. The data were adjusted for deuterons on enriched ^{64}Ni . No other adjustment in the data was required. Recent decay data are referenced and the monitor cross section data used for the measurement of the deuteron flux compare very well with IAEA evaluated data. The authors also measured ^{64}Cu yields in the 15-19 MeV energy window on

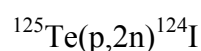
^{nat}Ni and on 96% enriched ^{64}Ni . These measurements compare well with the abundance ratios. However a preliminary integral calculation indicates that the measured thick target yield from ^{nat}Ni reported by the authors is still higher by a factor of 2 than the yield predicted on the basis of their reported cross sections.



Six data sets are available in the literature^[2, 3, 4, 5, 6, 7]. The data of McGee *et al* relies on very old monitor data for beam flux measurements and they seem low compared to the other sets. A recalculation of the cross sections, using IAEA evaluated monitor data, caused a slight upward shift on average but the resulting data set no longer resembled a plausible shape for an excitation function. Also the data point by Cohen *et al* is high. The authors report an error much larger than 25%. Neither of these data sets was selected for final fitting of the data.



Two data sets are available in the literature^[8, 9]. As pointed out by Bastian *et al* (2001), the data of Firouzbakht *et al* (1993) are too low. The latter authors also present thin target yield results. Cross section data recalculated by the evaluator on the basis of the reported thin target yield values compare well with those of Bastian *et al*.



Data are reported by three groups. Two of these groups present each a single data point at 300 MeV and 400 MeV respectively. Both these points are outside the scope of the present CRP. The data by Hohn *et al*^[10] shown form a good set in the energy range up to 100 MeV.

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**Progress Report on IAEA Research Agreement No. 12488
Measurement and Standardisation of Nuclear Reaction Cross Section
Data for Production of some Therapeutic Radionuclides**

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A research agreement between the IAEA and our institute dealing with the therapeutic radionuclides was signed in April 2003. This report describes briefly the status of the project as of November 2004.

Compilation and preliminary evaluation

Our responsibility stipulated work on four charged particle induced reactions, namely $^{64}\text{Ni}(p,n)^{64}\text{Cu}$, $^{70}\text{Zn}(p,\square)^{67}\text{Cu}$, $^{103}\text{Rh}(p,n)^{103}\text{Pd}$ and $^{124}\text{Te}(p,n)^{124}\text{I}$ processes. The work performed is summarized below.

For the $^{64}\text{Ni}(p,n)^{64}\text{Cu}$ and $^{70}\text{Zn}(p,\square)^{67}\text{Cu}$ reactions a literature search was carried out. All of the data are available in the EXFOR file. They were critically scrutinized according to the established practice. The most concordant set of data were selected and sent to the co-ordinating laboratory. An evaluation can now be performed.

Regarding the $^{103}\text{Rh}(p,n)^{103}\text{Pd}$ reaction, on the basis of a thorough experimental and theoretical study done jointly by the FZ Jülich and Debrecen University, an evaluated curve was presented, and recommended cross sections were given. It is suggested that the reported evaluated curve should be adopted.

As far as the $^{124}\text{Te}(p,n)^{124}\text{I}$ reaction is concerned, accurate cross section data were measured jointly by the FZ Jülich and ATOMKI Debrecen. A survey of the literature data was also carried out. All data are now with the co-ordinating laboratory and an evaluation can be performed.

Experimental studies

It was agreed at the 1st RCM in June 2003 that two reactions, namely $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ and $^{192}\text{Os}(p,n)^{192}\text{Ir}$, should be experimentally investigated at Jülich. During the intervening time, work on the $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ reaction was done jointly by the FZ Jülich and ATOMKI Debrecen. The investigated energy range extended from 5 to 45 MeV. Preliminary results will be presented at the 2nd RCM.

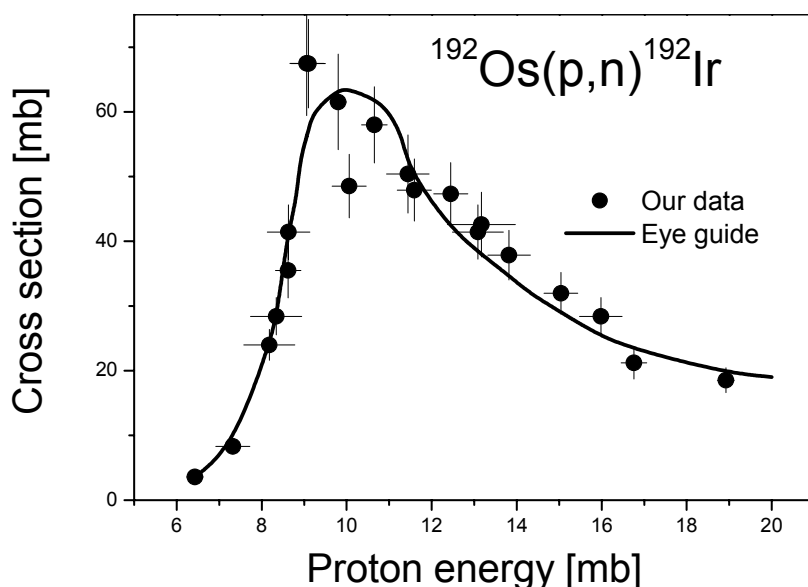


Fig. 1 Experimentally determined excitation function of the reaction $^{192}\text{Os}(p,n)^{192}\text{Ir}$.

The $^{192}\text{Os}(p,n)^{192}\text{Ir}$ reaction was studied from 6 to 19 MeV. Thin samples of 84.5 % enriched ^{192}Os were prepared by electrodeposition on Ni, and the conventional stacked-foil technique was used for cross section measurements. The results are shown in Fig. 1. The calculated yield of ^{192}Ir is low. A detailed discussion will follow.

CRP-related publications

- [1] HILGERS, K., SPAHN, I., SKAKUN, Y., COENEN, H.H., QAIM, S.M., New cross section data for production of the therapeutic radionuclides ^{64}Cu , ^{67}Cu , ^{40}Nd and ^{192}Ir , *Advances in Nuclear and Radiochemistry* (S. M. Qaim, H. H. Coenen, Editors), Forschungszentrum Jülich, Vol. 3, ISBN 3-89336-362-9 (2004), pp. 291 – 293.
- [2] HILGERS, K., QAIM, S.M., COENEN, H.H., New cross section data for production of the therapeutic radionuclides ^{64}Cu , ^{140}Nd and ^{192}Ir , *Proc. Int. Conf. Nuclear Data for Science and Technology*, Santa Fe, USA, 26 September to 1 October 2004, in press.
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**Progress report on the IAEA Research Contract No.12420
Calculation and Evaluation of Nuclear Reaction Cross-Sections for
Production of Therapeutic Radionuclides**

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The recent investigation results on the model calculations and evaluations connected with the creation of reference neutron and charged particles cross section database for therapeutic radioisotope production on Agency Research Contract No. 12420/R0/RBF are presented. Nuclear reaction models and codes are briefly outlined, which were used in these investigations, the examples of the calculation results are given. Method of statistical optimization of experimental data, based on discrete optimization with rational functions (Pade-approximation) is briefly described, and the results of evaluations of excitation functions are presented. The recommendations based on the systematically observed tendencies of experimental data on neutron induced threshold reactions are given also. Previous evaluations from well-known libraries ADL-3, JENDL-3, BROND-2, ENDF/B-VI, EAF-97 are analysed and discussed.

New calculations of (n,p) reaction cross sections for the $^{32}\text{S}(n,p)^{32}\text{P}$, $^{89}\text{Y}(n,p)^{89}\text{Sr}$ and $^{90}\text{Zr}(n,p)^{89}\text{Y}$ with GNASH code have been performed and new evaluations of BROND-3 library are discussed. New calculations of charged particle induced reactions according to the list of distribution of tasks discussed at the first CRP Meeting have been performed for the $^{186}\text{W}(p,n)^{186}\text{Re}$, $^{186}\text{W}(d,2n)^{186}\text{Re}$ and $^{226}\text{Ra}(p,2n)^{225}\text{Ac}$ with the ALICE-IPPE code.

The following publications were done in connection with CRP activities:

- [1] Calculation and evaluation of neutron induced threshold reaction cross sections for $^{32}\text{S}(n,p)^{32}\text{P}$, $^{89}\text{Y}(n,p)^{89}\text{Sr}$ and $^{90}\text{Zr}(n,p)^{89}\text{Y}$ reactions, DITYUK, A.I., MANOKHIN, V.N., and SHUBIN, Y.N., VANT (Voprosy Atomnoy Nauki i Techniki), issue 2, 2004.
- [2] Evaluation of cross section data for applications in accelerator driven energy systems and in production of medical radioisotopes, GAI, E.V., IGNATYUK, A.V., LUNEV, V.P., SHUBIN, Y.N., TITARENKO, N.N., has been presented at the International Conference NRC6, Aachen, Germany, 28 August–3 September 2004.
- [3] New data of Intermediate energy nuclear reactions for theory and medical applications, SCHOLTEN, B., KETTETRN, K., NORTIER, F.M., STEYN, G.F., SHUBIN, Y.N., SPELLERBERG, S., VAN DER WALT, N., QAIM, S.M., COENEN, H.H., has been presented at the International Conference NRC6, Aachen, Germany, 28 August – 3 September 2004.
- [4] HERMANNE, A., TARKANYI, F., TAKACS, S., SHUBIN, Y.N., “Experimental determination of cross section of d-induced reactions on ^{nat}Pd ”, International Conference on Nuclear Data for Science and Technology, 26 September–1 October, 2004, Santa Fe, New Mexico, USA.
- [5] HERMANNE, A., TARKANYI, F., TAKACS, S., SHUBIN, Y.N., “Experimental determination of cross section of alpha-induced reactions on ^{nat}Pd ”, International Conference on Nuclear Data for Science and Technology, 26 September -1 October, 2004, Santa Fe, New Mexico, USA.

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 "Measurement of activation cross sections of the proton-, deuteron- and alpha particle induced nuclear reactions on platinum. International Conference on Nuclear Data for Science and Technology, 26 September-1 October, 2004, Santa Fe, New Mexico, USA.
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- [9] TARKANYI, F., DETROI, F., MAHUNKA, I., UDDIN, M.S., HAGEWARA, M., BABA, M., SHUBIN, Y.N., DITYUK, A., „Excitation functions of proton induced on ^{nat}Sn : relevance to the production of ^{111}In and $^{114\text{m}}\text{In}$ for medical applications". International Conference on Nuclear Data for Science and Technology, 26 September-1 October, 2004 Santa Fe, New Mexico, USA.

**Progress Report on IAEA Research Agreement No. 12487
Review of Selected Cross-Sections and Fission Yields for
Production of Emerging Therapeutic Radionuclides**

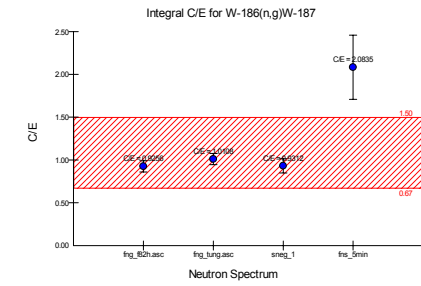
J.-Ch Sublet and O Serot

CEA Cadarache, DEN/DER/SPRC, 13108 Saint Paul Lez Durance, France

An accurate and complete knowledge of nuclear data is essential for the production of radionuclides for therapy in order to achieve the specific activity and purity required for an economical production followed by an efficient and safe clinical application. The capture reaction and fission yields pathways of a set of important radionuclide are analyzed with emphasis on the possibility of producing these emerging therapeutic radioisotopes through such routes. Since the capture reaction has the highest cross section at low incident neutron energies, a thermal reactor environment is foreseen as preferable to optimize productivity. These emerging radioisotopes are less commonly used but are potentially interesting for clinical application.

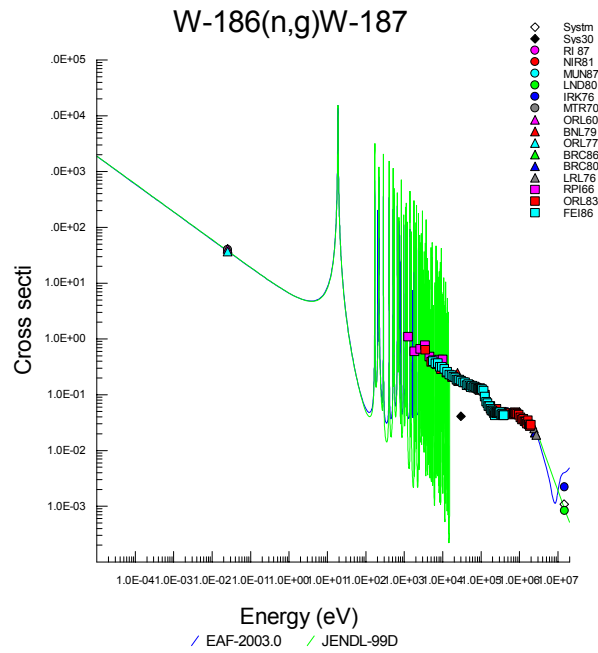
The ^{185}Re , ^{186}W , ^{187}W , ^{176}Lu isotopes capture and ^{67}Zn (n,p) channels are re-evaluated to assess the current data file quality and where possible, associated uncertainties, both of which are strongly energy dependant. ^{90}Sr , ^{131}I and ^{137}Cs fission yields of ^{235}U are re-visited. The decay data of their direct or semi-direct reaction products are assessed in order to place confidence in their safe and efficacious medical application. For example, for Cu-64 authorize the application of a combination of therapy and positron emission tomography. Integral experiments have been use, when available, to determine a quality score of each reaction. Such analysis is likely to allow the reactions to be prioritised as efficient routes of production and to establish if further evaluation or experimental studies are deemed necessary.

W 187 23.85 h 0.34% decay β^- 100 %



W-186 0.0253eV XS	
Barns	Δ Lab.
37.0	1.5 ORL77
35.4	8.0 MOL67
37.8	1.2 AGA66
38.5	8.0 MUN87
38.	15% JEFF-3.0/A

W-186 Resonance Integral			
E. Min.	Barns	Δ	Lab.
0.5	426.	32.	LRL78
0.5	490.	15.	ORL77
0.5	410.	47.	GHT74
0.5	345.	99.	BCK69
	519		JEFF-3.0/A



188-Re generator

Decay data viewer
[-] [x]

Nuclide :
[Ag-108m format]

Spin and parity : 0⁺

Mass : 187.95867 amu

Half-life : 6.0000E+06 ± 5.0000E+04

<Alpha> : 0.0000E+00 ± 0.0000E+00

<Beta> : 9.9600E+04 ± 1.0000E+03

<Gamma> : 1.8900E+03 ± 7.0000E+01

Number of decay modes : 1

Decay mode(s)	Branching ratio (%)
(b-) Re-188	100 %

188

W

74
114

Source : jef22_dec

Decay data

Biological hazard coefficients (Sv/Bq)

Ingestion : 2.1000E-09

Inhalation : 5.7000E-10

Source : ICRP72

Transport

A2 coefficient : 0.20000 TBq

Source : A2 VALUE

Clearance level

Clearance : 8.43882E+04 Bq/kg

Source : Calculated

Photon lines

Matter lines

Stable

Beta -

Beta +

Alpha

IT

SF

Proton

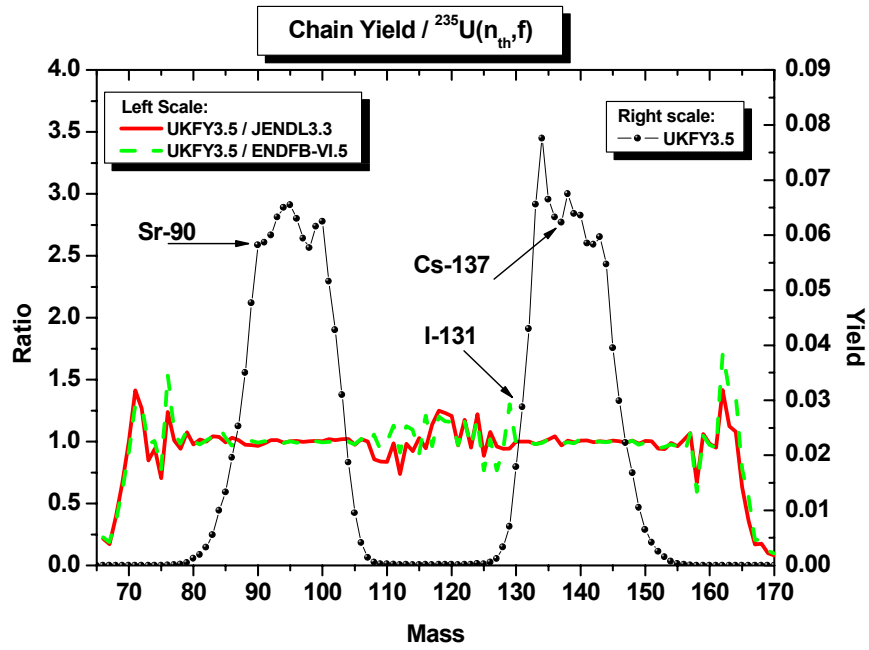
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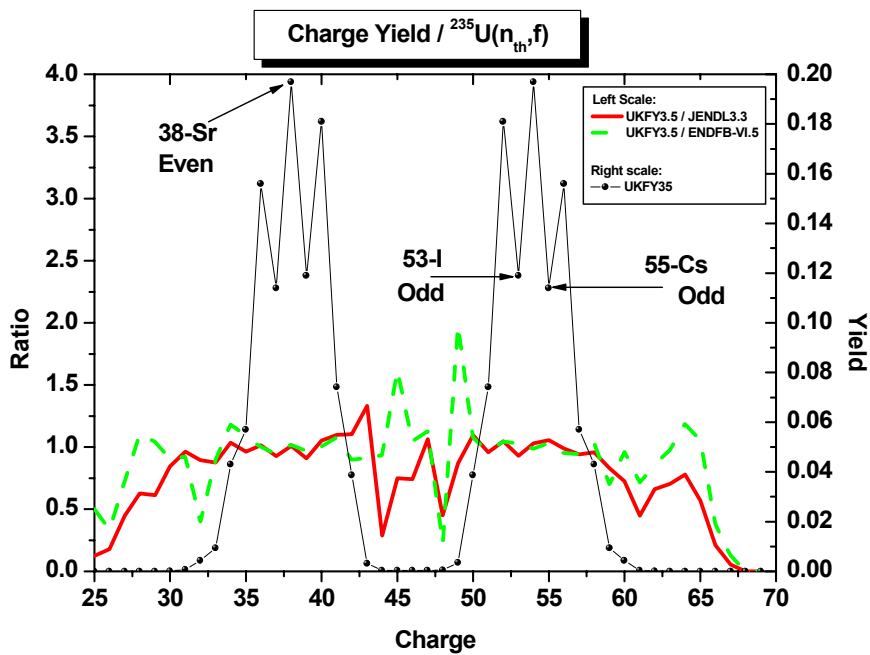
Get data

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U-235 fission yields : 0.0253 eV



U-235 fission yields : 0.0253 eV



**Progress Report on IAEA Research Contract No. 12419
Experiments and Data Evaluation by the ATOMKI group**

F.Tárkányi, S.Takács, F. Ditrói, F Szelecsényi, Z. Kovács, Z. Szűcs, I. Mahunka, J. Csikai.

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Introduction

In the present status report we summarize the results of our experimental and compilation work, performed with the aim to prepare recommended data for the most widely used therapeutic radioisotopes. We include only the participants from Debrecen. Co-authors from the collaborating institutes can be found in the related new publications.

New experimental result

All experiments assigned to ATOMKI have been successfully completed. The main partners in the measurements of nuclear data for production of therapeutic radioisotopes were: VUB Brussels, FZ Jülich, CYRIC Tohoku University.

The results were presented as posters at the NRC6 Conference in Aachen and at the ND2004 Conference in Santa Fe. The results will be published in conf. proceedings and in more extended format in different journals (NIM B, Applied Radiation and Isotopes, Radiochimica Acta). The summary of the experiments is collected in Table 1.

Additionally to the work in Table 1 we took also part in the measurement of the excitation function of the $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ reaction. The Jülich group coordinated this measurement. We made dedicated experiments to solve the problem of the disagreements in the production cross-section data of ^{103}Pd measured by X-ray and gamma-counting (see in summary). Our study of excitation functions of proton and deuteron induced reactions on Pt, Ir and Pd shows that possible Pt, Ir and Pd impurities in the used Rh target could not be the reason of the observed disagreement. The $^{66}\text{Zn}(p,2p)^{64}\text{Cu}$ and $^{68}\text{Zn}(p,x)^{64}\text{Cu}$ nuclear processes were investigated up to 100 MeV for production of ^{64}Cu . Activation cross sections of longer lived products of proton and deuteron induced nuclear reactions on zinc were measured, providing cross section data for production of ^{64}Cu and ^{67}Cu .

Compilation and evaluation

The compilation and critical analysis of the literature data for all reaction assigned to the Debrecen group have been completed ($^{103}\text{Rh}(d,2n)^{103}\text{Pd}$, $^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$, $^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$, $^{186}\text{W}(p,n)^{186}\text{Re}$, $^{186}\text{W}(d,2n)^{186}\text{Re}$, $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ reactions). For most of them theoretical calculation was also done. The comparison with the experimental data shows that fitting process is required to prepare recommended data in all cases.

Problems and recommendations

During the new measurements and the data compilations we met the following problems, which require in some cases additional experiments:

Cross sections

- There is unresolved discrepancy between the cross-section data of ^{103}Pd measured by X- and 357 keV energy gamma ray.
- There is an unresolved discrepancy between the cross-section data measured by the 511 keV annihilation gamma line and the 1346 keV gamma ray.
- The $^{116}\text{Cd}(p, 3n)$ reaction is more productive to obtain $^{114\text{m}}\text{In}$ compared to $^{114}\text{Cd}(p, n)$ and $^{114}\text{Cd}(d, 2n)$. The isotopic cross-section can be deduced from the available data on $^{\text{nat}}\text{Cd}(p, xn)^{114\text{m}}\text{In}$ and $^{114}\text{Cd}(p, n)^{114\text{n}}\text{In}$ reactions. We suggest to complete the CRP reaction list with this reaction.

Yields

- New experimental yield measurement for data validation seems to be reasonable for the $^{\text{nat}}\text{Cd}(p, x)^{114\text{m}}\text{In}$, $^{\text{nat}}\text{Cd}(d, x)^{114\text{m}}\text{In}$, $^{\text{nat}}\text{W}(p, x)^{186}\text{Re}$ and $^{\text{nat}}\text{W}(d, x)^{186}\text{Re}$ reactions.

Table 1. Cross-section data measurements for production of therapeutic radioisotopes in the frame of the present CRP

Target	Primary beam	Monitor reactions	Activity meas.	Reactions	Number of σ -points	Energy range (MeV)	Reference
^{nat}Bi , evaporated on Cu and Al backing, 1-4 μm thick	40 MeV α 40 MeV α	$^{nat}\text{Cu}(\alpha,x)^{65}\text{Zn}$, $^{nat}\text{Cu}(\alpha,x)^{66}\text{Ga}$	α -Si, γ -HpGe	$^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$	27	19.0-39.9	ARI (submitted), ND2004 proc. (submitted)
				$^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ (through ^{211}Po)	27	19.0-39.9	
				$^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ (through ^{207}Bi)	3	29.6-32.4	
				$^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$	14	31.0-39.9	
				$^{209}\text{Bi}(\alpha,x)^{210}\text{Po}$	18	25.0-39.9	
				$^{209}\text{Bi}(\alpha,x)^{210\text{cum}}\text{Po}$	17	25.0-39.9	
^{114}Cd (99.01 %) electrodeposited on Cu backing, 13.6 μm thick	16.0 MeV p 36.0 MeV p	$^{nat}\text{Cu}(\text{p},x)^{62,65}\text{Zn}$	γ -HpGe	$^{114}\text{Cd}(\text{p},n)^{114\text{m}}\text{In}$	34	4.9-35.8	NRC6 abstr.
^{nat}Cd foil, 15.56 μm thick	33 MeV p 70 MeV p 70 MeV p 80 MeV p	$^{nat}\text{Cu}(\text{p},x)^{62,65}\text{Zn}$, $^{56,58}\text{Co}$ $^{nat}\text{Al}(\text{p},x)^{22,24}\text{Na}$	γ -HpGe	$^{nat}\text{Cd}(\text{p},\text{xn})^{114\text{m}}\text{In}$ and others	47	5.9-77.6	NRC6 abstr., ND2004 proc. (submitted)
^{114}Cd (99.01 %) electrodeposited on Cu backing, 12.8 μm thick	21 MeV d	$^{nat}\text{Ti}(\text{d},x)^{48}\text{V}$, $^{nat}\text{Cu}(\text{d},x)^{65}\text{Zn}$	γ -HpGe	$^{114}\text{Cd}(\text{d},2n)^{114\text{m}}\text{In}$ and others	16	8.4-20.7	NRC6 abstr.
^{nat}Cd foil, 15.56 μm thick	21 MeV d 40 MeV d	$^{nat}\text{Cu}(\text{d},x)^{65}\text{Zn}$ $^{nat}\text{Al}(\text{d},x)^{22,24}\text{Na}$ $^{nat}\text{Ti}(\text{d},x)^{48}\text{V}$	γ -HpGe	$^{nat}\text{Cd}(\text{d},\text{xn})^{114\text{m}}\text{In}$ and others	25	5.1-39.8	NRC6 abstr., ND2004 proc. (submitted)
					25	5.1-39.8	

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