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Summary Report

Third Research Coordination Meeting on

Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production

IAEA Headquarters
Vienna, Austria

30 May – 3 June 2016

Prepared by

Alan L. Nichols
Departments of Physics
University of Surrey
Guildford, UK

F. Meiring Nortier
Los Alamos National Laboratory
New Mexico, USA

R. Capote Noy
IAEA Nuclear Data Section
Vienna, Austria

January 2017

IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

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Vienna International Centre
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Austria

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Abstract

A summary is given of the third and final IAEA research coordination meeting on "Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production". Participants re-assessed and reviewed their progress with respect to the completion of the measurements and evaluations of specific cross-section and decay data agreed at the previous RCM. Debate focused on cross-section studies for a reasonably wide range of targets and projectiles, along with the relevant recommended decay data for specific radionuclides. Options for the possible preparation and publication of peer-reviewed papers on the work were also discussed in some detail, and future related actions and exchanges of information were agreed to assemble such papers. Presentations and discussions are described in this report, along with listings of the progress, current status and plan to ensure completion of the various individual work programmes. All presentations are available on the webpage:

www-nds.iaea.org/index-meeting-crp/CHARPAR-3.RCM/3rd-rcm.htm

January 2017

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1. Introduction

One important aspect of IAEA work is to assist all member states in the peaceful application of nuclear science, of which one significant area is disease prevention/control/treatment particularly with respect to the adoption of diagnostic/therapeutic radionuclides in nuclear medicine and radiotherapy. The production routes and decay properties of all such radionuclides need to be well defined, but deficiencies exist, especially with respect to the optimum production of specific radionuclides, minimization/elimination of impurities, and adequate determination of various decay parameters.

The IAEA Nuclear Data Section has sponsored various consultants' meetings to discuss possible nuclear data requirements up to approximately 2025[1,2,3]. Specific recommendations from these three consultants' meetings were brought together in June 2011 to formulate and agree the scope, work programme and deliverables of a Coordinated Research Project designed to focus on further improvements to specific charged-particle monitor reactions and nuclear data for the most efficient production and characterisation of medical radionuclides. The first and second research coordination meetings were held at IAEA Headquarters from 3 to 7 December 2012 and 8 to 12 December 2014 respectively, at which agreement was reached concerning a wide range of well-defined work programmes to be implemented and reviewed regularly by the participants[4,5].

M. Venkatesh (Director, NAPC) welcomed the participants. She emphasised the need for sound links with medical specialists and their nuclear physicists in order to focus IAEA-NDS studies on the important nuclear data for the production and characterisation of radionuclides to be used in existing and future medical applications. Effectively, the significant efforts of the existing CRP are approaching their end-point, with the aim of producing an appropriate, improved database and related publications by 2017/18. Seventeen CRP participants (B.V. Carlson, J.W. Engle, A. Hermanne, A.V. Ignatyuk, M.A. Kellett, T. Kibédi, F.G. Kondev, O. Lebeda, T. Nagai, A.L. Nichols, F.M. Nortier, S.V. Suryanarayana and F.T. Tárkányi) attended (with apologies for absence from A. Luca, M. Hussain, G. Kim and I. Spahn), while the IAEA was represented by R. Capote (Scientific Secretary, Nuclear Data Section). F.T. Tárkányi (Institute of Nuclear Research, Hugarian Academy of Sciences (excitation functions)) and A.L. Nichols (University of Surrey, Guildford, UK (decay data)) were elected to co-chair the meeting, and A.L. Nichols and F.M. Nortier served as rapporteurs. The approved Agenda is attached (Appendix 1), as well as a list of all participants and their affiliations (Appendix 2).

2. Presentations

Presentations by the participants are available on IAEA-NDS web page www-nds.iaea.org/index-meeting-crp/CHARPAR-3.RCM/3rd-rcm.htm. A brief summary of the work scope and status associated with each presentation is outlined below.

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[1] R. Capote and A.L. Nichols, Consultants' Meeting on "High-precision beta-intensity measurements and evaluations for specific PET radioisotopes", 3-5 September 2008, IAEA report **INDC(NDS)-0535**, December 2008, IAEA, Vienna, Austria.

[2] R. Capote and F.M. Nortier, Consultants' Meeting on "Improvements in charged-particle monitor reactions and nuclear data for medical isotope production", 21-24 June 2011, IAEA report **INDC(NDS)-0591**, September 2011, IAEA, Vienna, Austria. Available online at https://www-nds.iaea.org/publications/indc/indc-nds-0591.pdf

[3] A.L. Nichols, S.M. Qaim and R. Capote, Technical Meeting on "Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data", 22-26 August 2011, IAEA report **INDC(NDS)-0596**, September 2011, IAEA, Vienna, Austria. Available online at https://www-nds.iaea.org/publications/indc/indc-nds-0596.pdf

[4] A.L. Nichols and R. Capote, Summary Report of First Research Coordination Meeting on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production, 3-7 December 2012, IAEA report **INDC(NDS)-0630**, February 2013, IAEA, Vienna, Austria. Available online at https://www-nds.iaea.org/publications/indc/indc-nds-0630.pdf

[5] A.L. Nichols, F.M. Nortier and R. Capote, Summary Report of Second Research Coordination Meeting on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production, 8-12 December 2014, IAEA report **INDC(NDS)-0675**,

April 2015, IAEA, Vienna, Austria. Available online at https://www-nds.iaea.org/publications/indc/indc-nds-0675.pdf

2.1. Reaction Cross Sections

2.1.1. Contribution of VUB-Brussels, A. Hermanne (Vrije Universiteit, Brussels, Belgium)

Between January and July 2015 datasets for the assigned reactions were prepared according to the recommendations of the second RCM of December 2014. The files contained numerical values and graphs of all compiled data and a selection of data to be fitted was made (reasons for de-selection were also given). Overall uncertainties on the cross-sections (and if available on the energy) were included for each reference, and as much as possible information on the contributing uncertainties (also systematic) was given. Where needed these uncertainties were added or adapted by the compiler (for instance 8% beam current). The adopted nuclear decay data were listed and checked against recommended and updated data (also those data provided in this CRP). A single EXCEL list of all selected sets with overall uncertainties was sent to Obninsk for fitting (also copies to IAEA and Debrecen)

Monitor reactions: a first approach to correlations between data sets was included (see last paragraph in Sub-section 2.2.1 of the second RCM (IAEA report INDC(NDS)-0675)). Deuteron beam monitoring: 11 reactions were sent along with additional data for Ti(d,x)^{46}Sc obtained from Lebeda, Spahn and Duchemin after the second RCM. Proton beam monitoring: 6 reactions were sent. Alpha beam monitoring (earlier assigned to Hussain): All data were sent, which included additional data from Kim.

Two other files handled by VUB were for the ^{69}Ga(p,2n)^{68}Ge (additional high energy data) and ^{112}Cd(p,2n)^{111}In reactions (our latest experiments and publication).

The data cut was set for the beginning of 2015, although more recent publications from Kim and Lebeda will still be included in these reactions, prompting the need for new fits. Additional data retrieved in publications in the next months will be used for validation of the selections and fits (e.g. ARRONAX (Cu,Ti,Ni+p), in review).

Examples of reactions for alpha monitoring were presented at the meeting, and discussed (Cu(α,x)^{67,66}Ga, ^{65}Zn, selection, graphs, correlation). The methodology for defining correlations was explained by means of two examples: Ni(d,x)^{58}Co and Ti(d,x)^{46}Sc. Experiments performed in collaboration with Debrecen over the last two years that are relevant to the CRP will be included in the data sets (Ag+d, Pr+d, Mo+α).

2.1.2. Experimental studies and data evaluations by the ATOMKI group, F.T. Tárkányi (Institute of Nuclear Research, Debrecen, Hungary)

As agreed at the previous CRP meeting, ATOMKI staff have performed experimental, compilation and evaluation work. Large sets of new experimental data were measured (Table 1), and practically all reactions compiled. Part of this work remains to be sent for fitting, while some of the promised additional experimental data is still awaited for consideration.

Compilations

Practically all reactions have been fully compiled. We have listed below only those reactions which were also compiled, but not sent for fitting before this third RCM.

Monitor reactions

^{3}He-induced reactions: ^{nat}Al(^{3}He,x)^{22,24}Na, ^{nat}Ti(^{3}He,x)^{48}V

Table 1. New CRP-related experimental data

Target	Reaction	E_{max}(MeV)	CRP-related product
Monitor reactions			
^{nat}Mo	$^{nat}Mo(p,x)^{96}Tc$	36	^{96}Tc
^{nat}Ti	$^{nat}Ti(p,x)^{46}Sc$	65	^{46}Sc
^{nat}Ni	$^{nat}Ni(p,x)^{57}Ni$	65	^{57}Ni
Diagnostic gamma emitters			
^{51}V	$^{51}V(p,n)^{51}Cr$	65	^{51}Cr
^{55}Mn	$^{55}Mn(p,x)^{51}Cr$	70	^{51}Cr
^{nat}Mo	$^{nat}Mo\ (p,2n)^{99m}Tc$ $^{nat}Mo\ (p,pn)^{99}Mo\text{-}^{99m}Tc$	36 36	^{99m}Tc $^{99}Mo\text{-}^{99m}Tc$
^{112}Cd	$^{112}Cd(p,2n)^{111}In$	37	^{111}In
^{112}Cd	$^{112}Cd(d,3n)^{111}In$	50	^{111}In
^{203}Tl	$^{203}Tl(p,3n)^{201}Pb\text{-}^{201}Tl$	42	^{201}Tl
Diagnostic positron emitters			
^{nat}Ni	$^{nat}Ni(p,x)^{55}Co$	65	^{55}Co
^{nat}Ni	$^{nat}Ni(d,x)^{55}Co$	40	^{55}Co
^{nat}Ge	$^{nat}Ge(d,x)^{72}As$	50	^{72}As
^{107}Ag	$^{107}Ag(\alpha,n)^{110m}In$,	27	^{110m}In
^{nat}Cr	$^{nat}Cr(\alpha,x)^{52}Fe\text{-}^{52}Mn$	36	$^{52}Fe\text{-}^{52}Mn$
^{59}Co	$^{59}Co(p,x)^{52}Fe\text{-}^{52}Mn$	70	$^{52}Fe\text{-}^{52}Mn$
^{55}Mn	$^{55}Mn(p,x)\ ^{52}Fe\text{-}^{52}Mn$	70	$^{52}Fe\text{-}^{52}Mn$
^{nat}Ga	$^{nat}Ga(p,x)^{68}Ge\text{-}^{68}Ga$	36	$^{68}Ge\text{-}^{68}Ga$
^{nat}Ga	$^{nat}Ga(d,x)^{68}Ge\text{-}^{68}Ga$	50	$^{68}Ge\text{-}^{68}Ga$
^{nat}Cd	$^{nat}Cd(^{3}He,x)^{110}Sn\text{-}^{110m}In$	27	$^{110}Sn\text{-}^{110m}In$
^{nat}In	$^{nat}In(d,x)^{110}Sn\text{-}^{110m}In$	50	$^{110}Sn\text{-}^{110m}In$
^{nat}In	$^{nat}In(p,x)^{110}Sn\text{-}^{110m}In$	70	$^{110}Sn\text{-}^{110m}In$
^{181}Ta	$^{181}Ta(d,x)^{178}W\text{-}^{178m}Ta$	40	$^{178}W\text{-}^{178m}Ta$
^{nat}Hf	$^{nat}Hf(\alpha,x)\ ^{178}W\text{-}^{178m}Ta$	40	$^{178}W\text{-}^{178m}Ta$
Therapeutic radioisotopes			
^{133}Cs	$^{133}Cs(d,x)^{131}Ba\text{-}^{131}Cs$	40	$^{131}Ba\text{-}^{131}Cs$
^{nat}Ba	$^{nat}Ba(d,x)^{131}Ba\text{-}^{131}Cs$	50	$^{131}Ba\text{-}^{131}Cs$
^{nat}Nd	$^{nat}Nd(d,x)^{140}Pm\text{-}^{140}Nd$	50	$^{140}Pm\text{-}^{140}Nd$
^{176}Yb	$^{176}Yb(d,x)^{177}Lu$	50	^{177}Lu

Diagnostic gamma emitters
Production routes of ^{51}Cr: $^{nat}Ti(^{3}He,xn)^{51}Cr$, $^{nat}Ti(a,xn)^{51}Cr$, $^{nat}V(p,xn)^{51}Cr$, $^{nat}V(d,xn)^{51}Cr$, $^{nat}Cr(p,x)^{51}Cr$, $^{nat}Cr(d,x)^{51}Cr$, $^{55}Mn(p,x)^{51}Cr$, $^{55}Mn(d,x)^{51}Cr$, $^{nat}Fe(p,x)^{51}Cr$
Diagnostic positron emitters
Production of *^{110m}In:* $^{110}Cs(p,n)^{110m}In$, $^{110}Cd(d,2n)^{110m}In$,$^{107}Ag(\alpha,n)^{110m}In$

Generators:
$^{62}Zn/^{62}Cu$ generator: $^{63}Cu(p,2n)^{62}Zn$, $^{63}Cu(d,3n)^{62}Zn$, $^{60}Ni(\alpha,x)^{62}Zn$ reactions
$^{68}Ge/^{68}Ga$ generator: $^{nat}Ga(p,xn)^{68}Ge$, $^{69}Ga(p,2n)^{68}Ge$, $^{71}Ga(p,4n)^{68}Ge$ reactions
$^{118}Te/^{118}Sb$ generator: $^{nat}Sb(p,x)^{118}Te$, $^{116}Sn(\alpha,2n)^{118}Te$, $^{115}Sn(\alpha,xn^{118}Te$ reactions
$^{122}Xe/^{122}I$ generator: $^{127}I(d,7n)^{122}Xe$, $^{127}I(p,6n)^{122}Xe$, $^{124}Xe(p,x)^{122}Xe$ reactions
$^{128}Ba/^{128}Cs$ generator: $^{133}Cs(p,6n)^{128}Ba$ reaction
$^{110}Sn/^{110m}In$ generator: $^{108}Cd(\alpha,2n)^{110}Sn$, $^{nat}In(p,x)^{110}Sn$ reactions
$^{178}W/^{178m}Ta$ generator: $^{181}Ta(p,4n)^{178}W$, $^{181}Ta(d,5n)^{178}W$, $^{nat}Hf(\alpha,x)^{178}W$ reactions

CRP-related publications from ATOMKI (2013-2016)

Publications, proceedings: 12 papers. *Conferences:* 6 presentations.

2.1.3. Review of the work done at NPI, 2015–2016, O. Lebeda (Nuclear Physics Institute, Rez, Czech Republic)

January 2015 to May 2016: NPI staff have performed the following agreed/relevant work at the Nuclear Research Institute of the CAS.

a) Re-measured in detail proton-induced reactions on natural molybdenum and obtained formation cross-sections for 25 radionuclides in the proton energy range of 6.9 to 35.8 MeV. The measurement focused particularly on the three reactions: monitoring reaction $^{nat}Mo(p,x)^{96m+g}Tc$ used by Levkovski in his extensive work from 1991, and the $^{100}Mo(p,2n)^{99m}Tc$ and $^{100}Mo(p,x)^{99}Mo$ reactions for alternative production of medically relevant ^{99m}Tc and ^{99}Mo. The data are based on absolute beam current measurement. These data were compared with all previously published cross-sections, corrected, if possible, for the difference in the abundance of ^{100}Mo in ^{nat}Mo used for conversion of elemental to isotopic cross-sections and for differing γ-ray emission probabilities. For the three above mentioned reactions, we selected the data sets we recommend for the fit and provided them to Ignatyuk and Tárkányi together with their preliminary recommended data. The available experimental elemental cross-sections of the $^{nat}Mo(p,x)^{94m}Tc$ reaction up to the threshold of the $^{95}Mo(p,2n)^{94m}Tc$ reaction were converted to isotopic data and provided to Carlson.
b) New experimental cross-sections were obtained for the proton-induced reactions on natural copper and titanium in the proton energy range of 6.5 to 36.0 MeV. These data are based on absolute beam current measurement. Data for the monitoring reactions $^{nat}Cu(p,x)^{62,63,65}Zn$ and $^{nat}Ti(p,x)^{48}V,^{46m+g}Sc$ were provided to Hermanne, and data for the $^{nat}Cu(p,x)^{58m+g}Co$ reaction were sent to Engle. The detailed measurement of the $^{nat}Cu(p,x)^{61}Cu$ reaction revealed a systematic difference of 14 ± 1 % between the activities of ^{61}Cu calculated via both dominant γ-lines (282.96 keV and 656.01 keV), which strongly implies that the decay scheme needs to be re-measured because re-evaluation of the existing measurements (Kondev) provides practically the same erroneous emission probabilities as used for the experimental evaluation.
c) The measurement of the cross-sections for the $^{75}As(p,3n)^{73}Se$ reaction was evaluated, but unfortunately the experiment was unsuccessful because the As targets were probably damaged in the beam. Subsequent NAA analysis revealed highly uneven thickness of the As layers. These cross-section measurements will be repeated, but they may not be performed until the end of this year.

The data for the $^{64}Zn(p,\alpha)^{61}Cu$ will be finally measured on natural zinc up to the threshold of the $^{66}Zn(p,\alpha 2n)^{61}Cu$. This is the only way to provide suitably thin targets of uniform thickness. This experiment may not be performed and evaluated until the end of 2016.

2.1.4. Nuclear data for medical radioisotope production by accelerator neutrons, Y. Nagai (National Institutes for Quantum & Radiological Science & Technology, Japan)

QST research proposals are identified with the determination of the neutron-induced reaction cross-sections of emerging diagnostic and therapeutic radioisotopes, as well as others that are well-established and commonly used in diagnosis and radiotherapy.

1. A new route is proposed to produce ^{99}Mo with a minimum level of radioactive impurity via the $^{100}Mo(n,2n)^{99}Mo$ reaction. The estimated yield of ^{99}Mo obtained

by means of a neutron beam generated via the $^{nat}C(d,n)$ reaction from a 40-MeV, 5 mA deuteron beam irradiating a metallic enriched ^{100}Mo sample (126 g) was 7.7 TBq (end of two-day irradiation, with a distance between the ^{nat}C target and ^{100}Mo sample of 1 cm). A route is also proposed to produce ^{67}Cu by the $^{68}Zr(n,np+d)^{67}Cu$ reaction with such neutrons.

Intense neutrons obtained by the $^{nat}C(d,n)$ reaction mentioned above have continuous energy spectra up to almost 40 MeV with a most probable energy of 14 MeV, and are emitted in a forward direction with respect to the deuteron beam. The energy and angular distributions of the neutrons were measured by Lhersonneau, *et al*. (*Nucl. Instrum. Methods Phys. Res*., **A603** (2009) 228).

2. The production yields of ^{99}Mo and ^{67}Cu together with impurity radionuclides by the reactions mentioned above have been determined using the neutrons generated at Takasaki Ion Accelerators for Advanced Radiation Application, QST.
3. An assessment of the cross-section data for the $^{130}Ba(n,\gamma)^{131}Ba$ reaction has also been made by using reactor neutrons relevant to the production of ^{131}Cs.

2.1.5. Cross-section studies and evaluation at LANL, J.W. Engle and F.M. Nortier (Los Alamos National Laboratory (LANL), USA)

As noted in the summary report of the second RCM, the LANL group assumed responsibility for the evaluation of fourteen nuclear reactions and the cross-section measurements of $^{nat}Cu(p,x)^{58}Co$ up to 100 MeV. Three of the reactions requiring evaluation are monitor reactions ($^{27}Al(p,x)^{22,24}Na$, $^{nat}Cu(p,x)^{58}Co$), six are important routes for the production of positron-emitter generators ($^{72}Se/^{72}As$, $^{82}Sr/^{82}Rb$ and $^{140}Nd/^{140}Pr$), and the remaining five are important to the production of radioisotopes applied in alpha therapy, such as ^{225}Ra, ^{225}Ac and ^{227}Th (long-lived parent of ^{223}Ra). About two thirds of these nuclear reactions are being evaluated for the first time, while the remaining third had been evaluated before as part of the work scope of previous CRPs, but now need re-evaluation. Following the methodology agreed upon at the first RCM all evaluations were completed by March 2015. This effort included thorough literature searches, review of more than 120 papers, compilation of more than 2000 data points, recording of and critical evaluation of the experimental methods, implementation of data adjustments where required, deselection of data in unavoidable cases, and submission of the evaluated data files to Ignatyuk.

Accelerator beam time was secured at the LANSCE LINAC for the measurement of $^{nat}Cu(p,x)^{58}Co$ cross sections along with other planned measurements up to 100 MeV, and one stacked foil irradiation was performed. Data analysis has been completed, and a manuscript has been submitted to NIMB. The LANL measurements as well as other new measurements from Lebeda and Kim were included in the evaluation.

It was again emphasized that the use of the $^{27}Al(p,x)^{24}Na$ monitor reaction at high energies (especially above 100 MeV) should be discouraged due to significant contribution by secondary neutrons. Instead monitor reactions of (p,xn) type in which secondary neutron contributions will not lead to erroneous proton-fluence values should be evaluated and recommended either as part of this CRP or as part of a follow-up CRP.

2.1.6. Experimental studies of the ^{100}Mo(p,x)^{99}Mo,^{99m}Tc excitation functions for proton energies from 14.3 to 20.3 MeV, Bremsstrahlung-averaged photoneutron cross sections from the ^{100}Mo(γ,n)^{99}Mo and ^{nat}U(γ,f)^{99}Mo reactions, and the ^{68}Zn(γ,p)^{67}Cu reaction at a Bremsstrahlung end-point energy of 15 MeV, S.V. Suryanarayana (Bhabha Atomic Research Centre (BARC), India) and A. Gopalakrishna (Medical Cyclotron Facility, Board of Radiation and Isotope Technology, India)

^{100}Mo(p,2n) reaction cross sections at five proton energies of 20.3, 19.0, 17.5, 16.0 and 14.3 MeV have been measured by means of the stacked-foil method with aluminium foils used as the energy degrader. 95%-enriched ^{100}Mo foils of various thicknesses were irradiated for 40.5 hours with the proton beam of the Pelletron accelerator, TIFR, Mumbai, India. After irradiation, the gamma activity was counted at six different cooling times (T_c of 10, 12.5, 21.5, 23.0, 27.0 and 31.5 h). Beam current and energy were determined from the ^{62}Zn/^{65}Zn activity ratio and the recommended cross sections for the monitor reactions of ^{nat}Cu (see IAEA-TECDOC-1211), resulting in an average beam current of 231 nA. The ^{99}Mo production cross sections were estimated at various energies from measured activities of the 181- and 739.5-keV gamma emissions. End of bombardment activities of the 140.5-, 181- and 739.5-keV gamma lines were used to estimate the ^{99m}Tc cross sections for all cooling times and proton energies. Similarly the ^{99}Mo cross sections were used as input to determine the four components contributing to 140.5-keV gamma-ray activity for all cooling times and proton energies mentioned above. Production cross sections for ^{99m}Tc as a function of energy were estimated from these data.

The Bremsstrahlung-averaged photoneutron cross section of ^{100}Mo(γ,n)^{99}Mo has been determined. Experiments were carried out at several international facilities. ^{99}Mo activities were produced in natural samples irradiated to give the ^{nat}Mo(γ,n)^{99}Mo and ^{nat}U(γ,f)^{99}Mo reactions. Photopeak areas for the 140.5- and 739.8-keV γ rays of ^{99}Mo from ^{238}U(γ,f) fission and ^{100}Mo(γ,n) reaction were measured, while ^{197}Au(γ,n)^{196}Au was used as the flux monitor by monitoring the 332.98- and 355.7-keV γ emissions of ^{196}Au. The expected ^{99}Mo activities were calculated per day per gram from the measured ^{99}Mo activities of the irradiated samples.

Experimental studies of the ^{68}Zn(γ,p)^{67}Cu reaction at a Bremsstrahlung end-point energy of 15 MeV exhibited a mismatch of 1.691 when compared with the equivalent cross sections taken from TENDL-2014. The FLUKA Monte-Carlo code was used to determine the flux, while the standardization cross sections for ^{197}Au(γ,n)^{196}Au monitor reaction came from JENDL-2004. This 69.1% underestimation of the experimental data is either because the TENDL2014 data are enhanced by a factor of 1.691, or neutrons from the Bremsstrahlung contribute to the missing 0.18 Bq via the ^{67}Zn(n,p)^{67}Cu reaction. However, ^{67}Zn abundance is ~ 4.0%, and the maximum cross section is ~ 2 mb as taken from the evaluated libraries. This contribution has not been estimated rigorously in the present study. A crude estimation is that the neutron spectrum for 15-MeV Bremsstrahlung gives a small contribution, and does not account for any mismatch because the neutron flux is ~ 10-3 neutrons/g.

2.1.7. Cross-section data assessments, B.V. Carlson (Instituto Tecnológico de Aeronáutica, Brazil)

Theoretical activities in the period were limited to refinements of the DDHMS and DBRKUP modules of EMPIRE-III, as well as preparatory modifications in the code to couple the output of the DBRKUP module to the PCROSS and DDHMS pre-equilibrium modules. Breakup-fusion and deuteron fusion components of deuteron-induced reactions couple only to equilibrium compound nucleus decay at present. The theoretical study of the pre-equilibrium emission of complex fragments has continued, that of pre-equilibrium deuteron emission in particular, but has not yet been implemented in the code.

A substantial amount of time was invested in the compilation and assessment of the reactions agreed upon at the first RCM. These are:
- ^{90}Zr(n,p)^{90}Y^{g+m} - data compiled, assessed and sent to Ignatyuk during the third RCM. Ground state data had already been compiled, assessed and evaluated by Ignatyuk in RRDF-2006 and IAEA Technical Reports Series No. 473.
- ^{64}Zn(n,p)^{64}Cu, ^{67}Zn(n,p)^{67}Cu, ^{68}Zn(n,x)^{67}Cu – data compiled but not assessed, as agreed at the second RCM.
- ^{89}Y(p,n)^{89}Zr - data compiled, assessed and sent to Ignatyuk during the third RCM.
- ^{94}Mo(p,n)^{94m}Tc - data compiled, assessed and sent to Ignatyuk one week after the third RCM. Additional data on natural Mo as received from Lebeda were included.
- ^{92}Mo(a,x)^{94m}Tc - data compiled, assessed and sent to Ignatyuk one week after the third RCM.
- ^{100}Mo(n,2n)^{99}Mo - data compiled, assessed and sent to Ignatyuk during the third RCM.
- ^{100}Mo(p,x)^{99}Mo, ^{99}Mo(p,2n)^{99m}Tc - compiled and assessed, but no final conclusion was reached. Completed with new data from Tarkanyi and Lebeda, and sent to Ignatyuk one week after the third RCM.
- ^{100}Mo(d,x)^{99}Mo, ^{99}Mo(d,3n)^{99m}Tc - data compiled, assessed and sent to Ignatyuk one week after the third RCM. Data on natural Mo was compiled and considered, but discarded.

2.1.8. Recommended cross sections and their uncertainties, A. Ignatyuk (Institute for Physics and Power Engineering (IPPE), Russia)

The unrecognized error-estimation method (UNERRES) developed at IPPE allows consistent evaluations of uncertainties and covariances for recommended sets of nuclear data (Gai, 2007). This method is being used to prepare CRP recommendations for selected sets of experimental data on the charged-particle induced reactions for medical applications.

All selected sets of experimental data sent to IPPE before May 2016 were analyzed, and preliminary versions of the recommended data were obtained. The following reactions were considered.

1. Monitor reactions:
   ^{27}Al(p,x)^{22,24}Na, ^{27}Al(d,x)^{22,24}Na, ^{nat}Ti(d,x)^{46}Sc and ^{48}V, ^{nat}Fe(d,x)^{56}Co, ^{nat}Ni(p,x)^{57}Ni, ^{nat}Ni(d,x)^{56,58}Co, ^{nat}Cu(p,x)^{58}Co and ^{62,63,65}Zn, ^{nat}Cu(d,x)^{62,63,65}Zn, ^{nat}Cu(α,x)^{66,67}Ga;
2. Diagnostic gamma emitters:
   ^{112}Cd(p,2n)^{111}In;
3. Positron emitters:
   ^{58}Ni(p,α)^{55}Co, ^{54}Fe(d,n)^{55}Co, ^{56}Fe(p,2n)^{55}Co, ^{66}Zn(p,n)^{66}Ga, ^{63}Cu(α,n)^{66}Ga, ^{93}Nb(p,x)^{90}Nb, ^{89}Y(α,x)^{90}Nb, ^{nat}Ge(p,xn)^{72}As, ^{75}As(p,3n)^{73}Se, ^{72}Ge(α,3n)^{73}Se, ^{76}Se(p,n)^{76}Br, ^{77}Se(p,2n)^{76}Br, ^{75}As(α,3n)^{76}Br, ^{86}Sr(p,n)^{86}Y, ^{88}Sr(p,3n)^{86}Y, ^{85}Rb(α,3n)^{86}Y, ^{89}Y(d,2n)^{89}Zr, ^{120}Te(p,n)^{120}I, ^{122}Te(p,3n)^{120}I;
4. Positron generators:
   ^{63}Cu(p,2n)^{62}Zn, ^{nat}Ga(p,xn)^{68}Ge, ^{69}Ga(p,2n)^{68}Ge, ^{75}As(p,4n)^{72}Se, ^{nat}Br(p,x)^{72}Se, ^{nat}Rb(p,xn)^{82}Sr, ^{85}Rb(p,4n)^{82}Sr, ^{55}Mn(p,4n)^{52}Fe, ^{nat}Ni(p,x)^{52}Fe, ^{133}Cs(p,6n)^{128}Ba, ^{nat}Ce(α,x)^{140}Nd, ^{141}Pr(p,2n)^{140}Nd;
5. Therapeutic alpha emitters:
   ^{232}Th(p,x)^{225}Ra, ^{232}Th(p,x)^{225}Ac, ^{232}Th(p,x)^{227}Ac, ^{226}Ra(p,2n)^{225}Ac,

$^{231}Pa(d,3n)^{230}U$, $^{231}Pa(p,2n)^{230}U$, $^{232}Th(p,x)^{227}Th$;
6. Therapeutic electron and X-ray emitters:
$^{131}Xe(p,n)^{131}Cs$, $^{133}Cs(p,3n)^{131}Ba$.

Recommended cross sections were estimated on the basis of the optimal Pade approximations, and the uncertainties of these recommended data were evaluated by means of the UNERRES approach. The results were sent to Capote (IAEA-NDS) and to the experts responsible for the data selections.

The remaining reactions included in the RCM tasks require additional revision of the experimental data and corresponding assessment of selected data. Final versions of the recommended data including uncertainties will be obtained after expert approval of the considered results.

Gai, E.V., Some Algorithms for the Nuclear Data Evaluation and the Covariance Matrix Construction, Voprosy Atomnoi Nauki i Tekhniki, ser. Nuclear Constants, 2007, is. 1, pp. 56-65; *http://vant.ippe.ru/images/pdf/2007/5.pdf2.2 Decay Data*

2.2. Decay Data

2.2.1. Nuclear data activities at the Argonne National Laboratory, F.G. Kondev (Argonne National Laboratory, USA)

An assessment of the half-life and absolute gamma-ray emission probabilities for ^{66}Ga has been completed. While an ENSDF evaluation by Browne and Tuli (*Nucl. Data Sheets* **111** (2010) 1093; cut-off date March 2009) recommended a half-life of $T_{1/2}$ = 9.49(3) h, a DDEP evaluation by Browne (cut-off date July 2003) recommended $T_{1/2}$ = 9.49(7) h. Two new articles reporting half-life measurements were published in the literature after these two evaluations had been performed: Severyn, *et al.* (*Phys. Rev*. **C82** (2010) 067301) reported $T_{1/2}$ = 9.304(8) h, while Gyurky, *et al.* (*Appl. Radiat. Isot.* **70** (2012) 278) reported $T_{1/2}$ = 9.312(32) h. These new half-life data are of high precision and the authors presented reasonable uncertainty budgets, including estimates of the systematic uncertainties. Importantly, they are also not discrepant, and therefore the newly recommended value for the half-life of ^{66}Ga is $T_{1/2}$ = 9.305(8) h, which is a weighted average of the results from Severyn, *et al.* and Gyurky, *et al.*

Decay-data evaluations within ENSDF (Browne and Tuli, *Nucl. Data Sheets* **111** (2010) 1093; cut-off date March 2009) and DDEP (Browne, cut-off date July 2003) contain consistent recommended values for the absolute γ-ray emission probabilities, as evident from the table below, which is not a surprise since the same evaluator was involved in both studies (Browne of LBNL). The main difference between the two evaluations is that the internal conversion coefficients required to normalize the ^{66}Ga decay scheme come from the BrICC code in the ENSDF evaluation (Band, *et al*. (2002) data), while older values from Rösel, *et al*. (1978) were used in DDEP. Thus, the ENSDF values for the γ-ray emission probabilities are recommended. No new measurements on the γ-ray emission probabilities have been published in the literature since the completion of the ENSDF evaluation (May 2009).

E_γ (keV)	**I_γ (%)[a]**	
	ENSDF	**DDEP**
833.5324 (21)	5.9 (3)	5.9 (5)
1039.220 (3)	37.0 (20)	37 (3)
2189.616 (6)	5.34 (29)	5.3 (4)
2751.835 (5)	22.7 (12)	22.7 (18)

[a] absolute γ-ray emission probabilities (number of γ rays per 100 decays).

Experimental spectroscopic studies of the decay of ^{66}Ga have continued at ANL. A suitable source was produced via the $^{66}Zn(p,n)$ reaction, an enriched thick target, and a 12-MeV proton beam. Singles and coincidence measurements have both been carried out by means of the Gammasphere spectrometer, as well as singles measurements with a HPGe detector. The decay scheme of ^{66}Ga is extremely complex, and a number of new γ rays have been identified and placed in an improved decay scheme. Full data analysis continues to be performed.

^{67}Cu has potential for a wide range of applications in cancer therapy and SPECT imaging. However, important decay properties that impact these applications have only been determined from a single measurement that was carried out about 60 years ago and reported without any uncertainties (Easterday, *Phys. Rev*. **91** (1953) 653). Therefore, we have completed a series of measurements with chemically-purified ^{67}Cu sources, produced via the $^{68}Zn(\gamma,p)$ reaction (*Appl. Radiat. Isot*. **70** (2012) 2377) in conjunction with γ-ray spectroscopy. Both singles and βγ-coincidence experiments were carried out using LEPS (γ rays) and PIPS (β^- and CE) detectors. Absolute β^- and γ-ray emission probabilities were determined and found to differ significantly when compared with presently adopted values. The newly measured decay data have been published in Phys. Rev. C., while a complete decay data evaluation of ^{67}Cu has also been carried out.

2.2.2. Decay data activities at the Laboratoire National Henri Becquerel (LNHB), M.A. Kellett (LNHB, CEA Saclay, France)

Laboratoire National Henri Becquerel (LNHB) is the French national standards laboratory. As reviewed below, LNHB staff have carried out a number of decay scheme evaluations for the CRP:

(a) ^{61}Cu was evaluated in 2013 for monitor reactions. Further half-life measurements would be beneficial. Although establishing the branching fraction to the ground state proved to be difficult, a self-consistent decay scheme has been formulated.

(b) The full decay scheme of positron-emitting ^{64}Cu was evaluated in 2012, and included a set of consistent results of measurements made by various metrology laboratories in the context of a EURAMET project. Any doubts about the emission intensity of the 1345.77-keV γ ray were dispelled, and the current evaluation is recommended for full adoption.

(c) The ^{230}U decay chain contains a number of potentially therapeutic alpha emitters, and the various decay schemes are being evaluated in collaboration with IFIN-HH staff. Six of the chain are being evaluated by LNHB, from ^{222}Ra down to ^{210}Po, while IFIN-HH are responsible for $^{230}U(\alpha)$ and $^{226}Th(\alpha)$. Complete evaluations have been finalised for $^{210}Po(\alpha)$, ^{210}Bi(predominantly β^-) and ^{210}Pb(predominantly β^-), while the evaluation of $^{214}Po(\alpha)$ is almost complete, $^{218}Rn(\alpha)$ is in progress, and $^{222}Ra(\alpha)$ has yet to be started. All evaluations are scheduled for completion by the end of 2016.

The evaluated data from LNHB and others participating in this CRP, are undertaken as part of the Decay Data Evaluation Project (DDEP). Availability includes the seven volumes of the Monographie-5 series published by the Bureau International de Poids et Mesures (BIPM), which can be downloaded free of charge from www.bipm.org/fr/publications/monographie-ri-5.html, with volume 8 now ready for publication (contains 32 evaluations, some from this CRP). A new "Mini Table of Radionuclides" containing the most important decay parameters was published in March 2015 through EDP Sciences. A total of 630 copies were sold in 2015 at a price of 25 € each. All evaluations are also available from the dedicated DDEP website (http://www.nucleide.org/DDEP_WG/DDEPdata.htm) where detailed evaluator comments are stored, as well as various ASCII file formats including the ENSDF format. Alternatively, a tool for gamma and alpha spectroscopists has been developed at the LNHB, providing a user interface allowing searches of the DDEP database to be made, which is available at http://laraweb.free.fr. This on-line tool has recently been enhanced with γ-γ coincidence information and the plotting of the decay schemes. Simplified decay schemes based on a user query can also be produced, for example, showing only the resulting gamma transitions above a certain threshold or within a certain energy range.

Work on producing a validated code, BETASHAPE, for calculating beta spectra was presented. Executable versions of this code for the major platforms are planned for general release in September 2016. This code has been partially validated at LNHB against Si(Li)/PIPS measurements undertaken as part of a PhD thesis (2011–2014) and cryogenic metallic magnetic calorimetry (MMC). A new PhD to continue the development of the Si(Li)/PIPS system is expected to start in October 2016, with further measurements of higher-order beta transitions. Both theoretical and experimental work in this area will continue at LNHB over the next three years, with some funding through the European Metrology Programme for Innovation and Research (EMPIR) project "Radionuclide beta spectra metrology (MetroBeta)", in collaboration with other European National Metrology Institutes (NMIs) and external partners.

Finally, details of the forthcoming 6th Workshop of the Decay Data Evaluation Project were given, which will take place on 19–22 September 2016 at the National Physical Laboratory, UK, in conjunction with three Working Groups of the International Committee for Radionuclide Metrology (ICRM). See http://ddep2016.eventbrite.co.uk/ for further details.

2.2.3. Improved nuclear decay data for emerging medical radioisotopes, A. Luca (National Institute of Physics and Nuclear Engineering Horia Hulubei (IFIN-HH), Romania) - as conveyed in absentia to R. Capote (IAEA-NDS)

Relevant research work performed at IFIN-HH since the 12 December 2014 has been focused on comprehensive ^{52m}Mn and ^{52}Mn nuclear decay data evaluations. The resulting files were sent to DDEP for peer-review in February and March 2016, and a progress report was sent to the IAEA at the end of March 2016.

^{52m}Mn decays 98.295(42)% by electron capture and positron emission to excited levels of ^{52}Cr, and by isomeric transition (IT) to the ground state of ^{52}Mn (1.705(42)%). The decay energy of the IT transition is 377.7 keV, and the half-life is 21.1(2) minutes. ^{52}Mn undergoes 100% electron capture and β^+ emission with a half-life of 5.592(3) days to various excited levels of ^{52}Cr - recommended half-life is the weighted mean of seven experimental values. A decay energy value for the ^{52}Mn EC/β^+ decay of 4711.2(19) keV was adopted from Wang, *et al*., *Chin. Phys.*, **C36** (2012) 1603. Spins, parities and level energies for both radionuclides were taken from the most recent mass-chain evaluation published for A = 52 (Yang Dong, Huo Junde, *Nucl. Data Sheets*, **128** (2015) 185). Energy balances for both of the decay schemes were tested by means of the SAISINUC tools, and the computed decay energies were found to be in good agreement with the equivalent Q values from the evaluations of Wang, *et al*. (2012).

Earlier CRP-related decay scheme data for ^{52}Fe have been presented at the 20th International Conference on Radionuclide Metrology and its Applications (ICRM 2015), held in Vienna, Austria, 8-11 June 2015, and recently published as A. Luca, Decay Data Evaluation Project: Evaluation of ^{52}Fe nuclear decay data, *Appl. Radiat. Isot.*, **109** (2016) 169-171.

Research work will continue at IFIN-HH on the ^{230}U and ^{226}Th nuclear decay data evaluations for completion before the end of 2016, as agreed at both the second and third research coordination meetings.

2.2.4. Decay data evaluations: ^{76}Br, ^{99}Tc^{m}, ^{99}Mo/^{99}Tc^{m}, ^{103}Pd/^{103}Rh^{m}, ^{111}In/^{111}Cd^{m}, ^{120}I and ^{131}Cs, A.L. Nichols (University of Surrey, Guildford, UK)

As reported previously, agreed CRP assignments for ^{63}Zn, ^{73}Se, ^{89}Zr and ^{94}Tc^{m} decay-data evaluations have been completed, approved and placed on the LNHB DDEP web site. Furthermore, ^{76}Br and ^{131}Cs decay-data evaluations were completed in 2015 and are currently undergoing review, while the ^{120}I decay-data evaluation has been underway from late 2015 into 2016. Nuclear decay-data evaluations have also been re-visited for ^{99}Mo/^{99}Tc^{m} in equilibrium, pure ^{99}Tc^{m}, ^{103}Pd/^{103}Rh^{m} and ^{111}In/^{111}Cd^{m} in support of the Auger-electron modelling studies by Kibédi and co-workers (Australian National University, Canberra).

^{76}Br ($T_{½}$ = 16.14(13) h) decays by 100% electron capture/β^+ decay (Q(EC) = 4963 (9) keV) to various excited nuclear levels and the ground state of ^{76}Se (stable). A reasonably well-defined decay scheme has been derived from four sets of spectral gamma-ray measurements. Considerable effort has been expended to incorporate many previously unplaced γ-ray transitions in the proposed decay scheme. Thus, thirty-five previously unplaced γ rays have been introduced into the recommended decay scheme which consists of 42 EC/24 β^+ transitions and 161 gamma-ray transitions (along with five unplaced gamma-ray emissions). Both in-depth γ singles and γ-γ coincidence studies would be beneficial in determining the absolute γ-ray emission probabilities and their placement in order to more confidently determine the detail of the rather complex decay scheme, along with total absorption gamma-ray spectroscopy (TAGS) to ensure a more confident treatment of the high-energy γ emissions and associated higher-energy nuclear levels involved in the EC/β^+ decay of ^{76}Br.

^{99}Tc^{m} ($T_{½}$ = 6.0070(8) h) undergoes 99.9963(6)% IT decay to the ground state of ^{99}Tc (Q_{IT} = 142.6832(11) keV) and 0.0037(6)% β^- decay to specific excited states and the ground state of ^{99}Ru (Q_{β^-} = 437.8 (11) keV). ^{103}Pd/^{103}Rh^{m}: ^{103}Pd ($T_{½}$ = 16.972(16) d) decays almost 100% by electron capture decay (Q(EC) = 503.3(8) keV) to the metastable excited state of ^{103}Rh^{m}, followed by IT decay ($T_{½}$ = 56.115(16) min) to the ground state of ^{103}Rh (Q(IT) = 39.753(6) keV). ^{111}In/^{111}Cd^{m}: ^{111}In ($T_{½}$ = 2.8049(5) d) decays by 100% electron-capture decay (Q_{EC} = 862(4) keV) to the metastable and ground states of ^{111}Cd, with ^{111}Cd^{m} undergoing 100% IT decay ($T_{½}$ = 48.50(9) min) to the ground state (Q_{IT} = 396.214(21) keV). ^{131}Cs ($T_{½}$ = 9.869(16) d) undergoes 100% EC decay to the ground state of ^{131}Xe (Q_{EC} = 355(5) keV). These four recommended data sets were forwarded to Kibédi (ANU), whereby Auger-electron and X-ray spectral calculations have been undertaken by means of the BrIccEmis code developed at ANU.

^{99}Mo/^{99}Tc^{m} in equilibrium: an extremely substantial number of dedicated references were assembled (over 150), and a full decay-data evaluation was completed in June 2015. ^{99}Mo ($T_{½}$ = 65.954 hours) undergoes 12.4(2)% β^- decay to the ground state of ^{99}Tc (Q(β^-) = 1357.8 (9) keV) and 87.6(2)% β^- decay to the ^{99}Tc^{m} metastable state ($T_{½}$ = 6.0070 h, Q_{IT} = 142.6832 (1) keV and Q(β^-) = 437.8 (11)). The β^- decay of ^{99}Mo is dominated by the β^- transition to the metastable state, while ^{99}Tc^{m} undergoes > 99.99% IT decay (Q_{IT} = 142.6832 (1) keV) primarily in the form of a two-gamma cascade (2.1726- and 140.51-keV gamma transitions). A reasonably well-defined decay scheme can be derived for ^{99}Mo β^- decay which is based on 11 β^- emissions and 37 gamma transitions (along with three unplaced gamma-ray emissions). The small β^- mode of decay of ^{99}Tc^{m} is identified with three low-intensity β^- emissions and three gamma-ray transitions, while the dominant IT decay consists of three gamma transitions (and significant conversion-electron emission from the 2.1726-keV E3 gamma transition). Parent ^{99}Mo (half-life of 65.954(19) h) in radioactive equilibrium with daughter ^{99}Tc^{m} (half-life of 6.0070(8) h) gives ^{99}Tc^{m} activity/^{99}Mo activity of 1.1002(5). Absolute β^- emission probabilities of ^{99}Mo were derived from the population-depopulation balances of the relative gamma-ray emission probabilities, their theoretical internal-conversion coefficients, and a normalization factor of (0.1214 ± 0.0012) for the gamma-ray emissions. β^- decay to the 761.78-, 181.09-, 140.51-keV and ground-state levels of ^{99}Tc were assumed to be zero on the basis of the spin-parity assignments of these particular nuclear levels and the resulting transition type, while the lack of β^- decay to the 534.43-keV arose from the observed population-depopulation balance of the relevant gamma transitions.

^{120}I ($T_{½}$ = 81.8(11) min) decays by 100% electron capture/β^+ decay (Q(EC) = 5615 (15) keV) to various excited nuclear levels and the ground state of ^{120}Te (stable). This on-going decay-scheme evaluation began in December 2015, and will contain throughout 2016. While previous such studies have placed 82 γ-ray transitions, over 70 remain unplaced and merit further quantification and resolution. Even at this rather early stage of the evaluation, the existing assessment appears to show that further in-depth γ singles and γ-γ coincidence studies would be beneficial in determining the absolute γ-ray emission probabilities and their placement in order to assist in defining the detail of the rather complex decay scheme more clearly. Total absorption gamma-ray spectroscopy (TAGS) would also ensure a more confident treatment of the high-energy γ emissions and associated higher-energy nuclear levels involved in the EC/β^+ decay of ^{120}I.

2.2.5. Auger-electron emission rates for medical radioisotopes – a 21st century physics perspective, T. Kibédi (Australian National University, Canberra, Australia)

A new stochastic model of atomic radiations from nuclear decay is being developed to evaluate the detailed energy spectra of Auger electrons and X-rays (B.Q. Lee, T. Kibédi, A.E. Stuchbery, *EPJ Web of Conferences*, **91** (2015) 00007). Atomic vacancies are created either by electron-capture decay or by internal conversion, followed by a vacancy cascade. The recombination process continues until all atomic vacancies reach the valence shell. Fixed Auger and X-ray transition rates taken from the EADL database are used in the current model. Extensive calculations have been carried out to benchmark the new model for comparison with experimental data on (a) atomic radiation spectra and (b) charge state distribution of ions recoiling into vacuum.

New collaborations have been established over the previous two years:

- University of Malmö (Sweden) and University of Lisbon (Portugal) on calculation of atomic radiation rates by means of GRASP2k/RATIP and MCDFGME;
- University of Oxford (UK) and Peter MacCallum Cancer Centre (Australia) on dose rate calculations of Auger-emitting radioisotopes;
- JINR, Dubna (Russia) on calculation of K and L Auger-electron spectra.

ANU results has been published in several papers, as well as being presented as invited talks at the Auger-2015 conference and the 14th International Workshop on Radiation Damage to the DNA, March 2016, Melbourne, Australia.

3. Discussions

3.1. Decay data

Individual responsibilities for the various decay data evaluations were initially discussed, and agreement was reached on the current status and future work to complete such studies by the end of calendar year 2016 (see Table 2).

Table 2: Second RCM Actions, and Status of Decay Data Evaluations, 31 May 2016.

Key to listed initials: M.A. Kellett (MAK), T. Kibédi (TK), F.G. Kondev (FGK), A. Luca (AL) and A.L. Nichols (ALN)

Decay scheme	Actions/Status	Location*
Monitor reactions		
Cu-61	MAK evaluation completed pre-second RCM	DDEP
Zn-62	no volunteer within CRP - adopt ENSDF	ENSDF
Zn-63	ALN evaluation completed pre-second RCM	DDEP
Diagnostic γ emitters: Auger electrons and X-rays		
Cu-67	FGK measurements and evaluation: **Action completed 2015**	FGK
Mo-99/Tc-99m	ALN evaluation and X/Auger study of pure Tc-99m: **Action completed 2016**	ALN
In-111	ALN evaluation and X/Auger study: **Action completed 2016**	ALN
Positron emitters		
Fe-52	AL evaluation completed pre-second RCM	DDEP
Mn-52m,g	AL evaluations: **Action completed 2015/16**	(DDEP)
Cu-64	MAK re-evaluation completed pre-second RCM	DDEP
Ga-66	FGK measurements and assessment completed, with provision of recommended half-life and absolute emission probabilities of most prominent γ rays: **Action completed 2015**	FGK
As-72	no volunteer within CRP - adopt ENSDF	ENSDF
Se-73	ALN evaluation completed pre-second RCM	DDEP
Br-76	ALN evaluation: **Action completed 2015**	(DDEP)
Y-86	BNL-NNDC measurements; awaiting release of results	(FGK)
Zr-89	ALN evaluation completed pre-second RCM	DDEP
Tc-94m	ALN evaluation completed pre-second RCM	DDEP
I-120	**ACTION: ALN evaluation still underway 2016**	(DDEP)
Ti-44 (half-life)	FGK half-life evaluation completed pre-second RCM	half-life: FGK decay scheme: ENSDF
Therapeutic α emitters: complete U-230 decay chain		
U-230	**ACTION: AL evaluation still underway 2016**	(DDEP)
Th-226	**ACTION: AL evaluation still underway 2016**	(DDEP)
Ra-222	**ACTION: MAK evaluation still underway 2016**	(DDEP)
Rn-218	**ACTION: MAK update still underway 2016**	(DDEP)
Po-214	**ACTION: MAK update still underway 2016**	(DDEP)
Pb-210	MAK update: **Action completed 2015**	DDEP
Bi-210	MAK update completed pre-second RCM	DDEP
Po-210	MAK update completed pre-second RCM	DDEP
Auger-electron and X-ray emitters		
Ta-178g and m	**ACTION: FGK (low-spin 1^+)/ALN (high-spin 7^-) evaluations to be undertaken in 2016 in preparation for X/Auger study**	(FGK/ALN)
Pd-103	ALN evaluation and X/Auger study: **Action completed 2016**	ALN
I-125	TK evaluation and X/Auger study: **Action completed 2016**	TK
Cs-131	ALN evaluation and X/Auger study: **Action completed 2016**	ALN

* Existing source of CRP decay data – future proposed source of CRP decay data given in parentheses; DDEP = Decay Data Evaluation Project, ENSDF = Evaluated Nuclear Structure Data File.

Eight complete decay schemes remain to be evaluated out of an original commitment of 27 radionuclides: ^{120}I, ^{178}Ta (^{178}Ta and ^{178}Ta^{m}) and the remaining balance of the ^{230}U decay chain (^{230}U, ^{226}Th, ^{222}Ra, ^{218}Rn and ^{214}Po):

Kellett – ^{222}Ra, ^{218}Rn and ^{214}Po;

Kondev and Nichols – ^{178}Ta (agreed: Kondev to evaluate low-spin (1^+) decay data, with a half-life of 9.3 min; and Nichols to evaluate high-spin 7^- decay data, with a half-life of 2.3 h);

Luca – ^{230}U and ^{226}Th;

Nichols – ^{120}I.

As noted at the second RCM, ^{86}Y finds application as a positron-emitting analogue of the pure β^--emitting therapeutic ^{90}Y radionuclide, thereby providing a means of undertaking sound dose distribution studies of the ^{90}Y. Under these promising circumstances, several PET-cyclotron companies have adapted and upgraded their facilities for the production of ^{86}Y to combine with reactor-produced ^{90}Y. Kondev has taken responsibility to provide recommended decay data for ^{86}Y, and noted the following developments:

- Argonne National Laboratory tandem accelerator has been dismantled, and is therefore unavailable for spectral measurements;
- opportunity exists for irradiations at the University of Notre Dame to prepare ^{86}Y sources;
- NNDC staff in collaboration with co-workers at the BLIP isotope production facility at Brookhaven National Laboratory have been granted approval to study the γ decay of ^{86}Y by means of the large Gammasphere array of 100 HPGe detectors located at the Argonne National Laboratory.

ACTION: Kondev to maintain communications with NNDC/ANL staff as to their ^{86}Y decay-data studies with Gammasphere, along with subsequent availability of data.

On completion, each of the recommended decay data files will be forwarded immediately by the CRP participant to Roberto Capote (IAEA–NDS) – “completion” defined as “fully evaluated, reviewed and approved”. Cross-section measurements for the CRP should involve adoption of all half-life and relevant γ and X-ray emission probabilities (intensities) as provided by Capote on request of the cross-section measurer.

Following on from early debate in the plenary sessions, the decision was unanimously taken to prepare a comprehensive decay data paper for appropriate open publication that would cover all of the decay-data studies initiated by the on-going coordinated research project (CRP), with completion envisaged no later than mid-2017. Necessary recommended decay data will also be provided for adoption in all related cross-section studies for (a) monitor reactions, (b) diagnostic radionuclides, and (c) therapeutic radionuclides within the CRP. Depending on the existing status of individual radionuclides, the sources of these decay data will be either CRP evaluations (preferred) when available, or from ENSDF.

The agreed format for the resulting decay database will be ENSDF, and various tools have been and will be used to check and develop good consistency (e.g. GABS, GTOL). Preparation of the proposed peer-review journal publication will include the adoption of a newly existing ENSDF drawing package for the production of full decay scheme figures. Furthermore, various decay parameter plots will need to be developed to clarify the nature of some of the evaluation procedures (e.g. to display rejected and adopted data plotted in conjunction with the recommended value with uncertainty limits).

ACTION: all decay-data evaluators to provide Kondev with their recommended decay-scheme data sets in ENSDF format.

ACTION: Kondev to employ the new ENSDF drawing package to produce full representations of the individual decay schemes, and such figures to be incorporated into the proposed decay data paper and other CRP-related publications when appropriate.

Issues identified as needing to be addressed:

1) ^{61}Cu – cross-section studies of the ^{nat}Cu(p,x)^{61}Cu monitor reactions suggest that the recommended absolute γ-ray emission probabilities are inconsistent and incorrect. Under these particular circumstances, new measurements of the γ-ray emission probabilities are required, possibly in a future decay data programme or CRP.
2) ^{67}Cu – an important new measurement and subsequent evaluation requires that all CRP cross-section studies and other relevant cross-section data included on the IAEA medical portal need to be adjusted/re-calculated (**ACTION**: all relevant CRP cross-section

participants to act accordingly, and Capote to correct any other relevant reactions contained within the IAEA medical portal).

3) ^{82}Sr (half-life of 25.35 d) – an intensity of 15.08% has been recommended for the 776-keV gamma ray of the short-lived ^{82}Rb daughter (half-life of 1.265 min) in an ENSDF evaluation by Tuli (*Nucl. Data Sheets*, **98** (2003) 209), resulting in the need to undertake a downward adjustment of 10% to IAEA-recommended cross sections for the production of ^{82}Sr. Furthermore, a subsequent measurement of the absolute intensity of the 776-keV gamma ray has furnished a value of 14.93(37)%, in very good agreement with the this evaluated value (Gross *et al*., *Phys. Rev*., **C 85** (2012) 024319). Almost all cross-section measurements published to the present time have adopted earlier intensity values ranging from 13.0% to 13.6%. Recommended data produced by the current CRP must involve the implement of this significant data change to adopt the most recently recommended value of 15.08(16)%. Although recent high-precision gamma-ray spectroscopic studies have revealed a significantly more complex decay scheme for ^{82}Rb, impact on the absolute intensity of the 776-keV gamma-ray emission and dosimetry characteristics is judged to be minimal (Nino *et al*., *Phys. Rev*., **C 93** (2016) 024301).
4) Consider quantification of Auger-electron and X-ray emission uncertainties, and their propagation through Monte-Carlo calculation (**ACTION**: Kibédi);
5) Validation of the BrIccEmis code for Auger-electron and X-ray decay data calculations, for which an appeal was made for the forwarding of suitable measurements of Auger-electron and X-ray spectra (**ACTION**: all CRP participants to forward suitable measured spectral data to Kibédi).

Within the CRP, the cross-section specialists who are working on the various production routes to achieve optimum yields and reduce radionuclidic impurities require only recommended half-lives, the decay modes and a limited number of γ and X-ray absolute emission probabilities (normally the most intense). However, thought also need to be given to the efficacious use of medical radionuclides with respect to determining and implementing the desired dose rates to the patient as well as those staff administrating various forms of diagnostic and therapeutic irradiation and radiopharmaceuticals to such patients. Under such circumstances, the recommendation of accurate and complete decay schemes is merited to ensure reasonably accurate dosimetry studies.

3.2. Cross sections

The work scope of the assignments agreed to at the first research coordination meeting (IAEA report INDC(NDS)-0630) includes an unusually long list of nuclear reactions to be evaluated. Detailed discussions on the status and remaining work were held after the presentations by the participants. The resulting status updates and actions are recorded in Tables 3 to 8. These extensive tables represent the equivalent summaries and on-going activities/actions for the derivation of recommended excitation functions to assist in achieving the optimum yields and purity of the desired radionuclides.

A few important points of discussion are highlighted here:

- Three CRP participants, responsible for specific cross-section evaluations, could not attend the third RCM. The assessment of these assigned reactions remains uncertain and incomplete, and therefore IAEA-NDS staff made arrangements to re-assign this work in order to complete to schedule.
- Some discussion focused on Sr-82 which could be produced from natural rubidium or enriched Rb-85. It was agreed that the evaluation and fitting of the relevant data sets should take into account an important additional requirement, i.e., the final recommended cross sections must reflect and be consistent with the Rb-85 content of the targets. This requirement also applies to other cross sections in this CRP where nuclear reactions on both natural and enriched targets are being evaluated.

- Another important point of note involves the adoption of a recommended half-life that has evolved after a series of cross-section measurements have been performed. In production cross-section measurements, the half-life is used to quantify the relevant radionuclide at the end of a controlled bombardment in order to determine its formation cross section, taking into account decay during and after bombardment. However, timing information such as bombardment time, post bombardment decay time before quantification and counting time, are not provided by authors. Under these circumstances, existing cross-section data for a particular radionuclide cannot be corrected by the CRP experimentalists if a new half-life value is recommended after their studies.
- Following on from earlier discussions it was decided to prepare three separate nuclear cross-section data papers for appropriate open publication that would present the assessment work and recommended data produced by the on-going coordinated research project (CRP), with completion envisaged no later than mid-2017. The respective topics of the three papers will cover monitor reactions, therapeutic radionuclides and diagnostic radionuclides.

4. Recommendations

Progress and completion were defined in terms of individual data sets, measurements and subsequent evaluations, as shown in the relevant columns of Tables 2 to 8. All resulting actions constitute the means of obtaining all important components of the final database for delivery and assembly in 2016 prior to the envisaged completion of the on-going coordinated research project:

<u>Decay data</u>:

- Compile and evaluate decay data, and deliver recommended data sets by the end of 2016
  - evaluate and select preferred data, and provide reasons for data rejection;
  - provide full bibliographic lists in the style of IAEA Technical Reports Series No. 473;
  - recommended data and any comment files to be reviewed, with final copies sent to Capote (IAEA-NDS);
  - final database release to be in ENSDF format.
- Provide Auger-electron data for agreed specific radionuclides with good accuracy and detail and prior to incorporation in the recommended decay-data files
  - suitable modelling code has been developed (Kibédi, *et al.*);
  - compilation and evaluation of Auger-electron data with respect to the modelling process, and provision of recommended Auger-electron decay data in 2016 for their timely insertion in the relevant files of the final database.

<u>Cross sections</u>:

During the discussions of the various cross-section studies outlined above, tables of activities and actions were prepared and agreed (Tables 3 to 8). The general tasks for the generation of recommended data were agreed at the first CRM:

- Compile reaction data, and assess and deliver files for evaluation and fitting before the third research coordination meeting. Assessed data should be provided in list form (EXCEL file) with indication of overall uncertainty for each data point. Correlations between data points may be provided for monitor reactions, if available. These EXCEL files should consist of (1) compiled data, (2) selected and corrected data with uncertainties (and correlations for monitor reactions), and (3) rejected data.
  - compile, assess, correct and select preferred data including uncertainties, providing reasons for data rejection;
  - send the files to Ignatyuk (IPPE), with a copy to Capote (IAEA-NDS);
  - evaluated data produced by Ignatyuk will be sent to Tárkányi, with copy to Capote (IAEA-NDS);
  - yields will be calculated by Tárkányi from evaluated data provided by Ignatyuk.

Other issues:

Capote will present an invited paper of 20 minutes at the international nuclear data conference, ND2016, Bruges, Belgium, in September 2016. The contents of this paper will cover all aspects of the coordinated research project – cross sections and decay data; measurements and evaluations. Effort would be required to pull together both a paper for publication in the proceedings and a suitable Powerpoint presentation. Some of the former material could be extracted from the minutes of the RCM meeting(s), while suitable Powerpoint images had already been composed and could be developed further (e.g. see Nichols, presentation at CARM2015, UK Conference on Applied Radiation Metrology). Authorship of the ND2016 paper would be based on all recognised CRP participants.

Concern was expressed as to the need and means of defining the scope and aims of the coordinated research project in the proposed peer-reviewed technical papers to be submitted for publication in the public domain. Nichols pointed out that such a description has already been written in a slightly abbreviated form as the introduction(s) to the minutes of the three research coordination meetings, and could be adopted with good conscience in the proposed publications specified in Sub-sections 3.1 and 3.2. Suitable and realistic deadlines for the preparation of the various envisaged papers are also required:

1) monitor cross sections – measurements and evaluations, plus their evaluated decay data;
2) cross sections of diagnostic radionuclides – measurements and evaluations, plus their evaluated decay data;
3) cross sections of therapeutic radionuclides – measurements and evaluations, plus their evaluated decay data;
4) recommended decay data - measurements (e,g. ^{67}Cu, ^{66}Ga) and all evaluations.

ACTION: Capote to pursue the proposal to publish comprehensively within appropriate journal(s) in the public domain (e.g. *Nucl. Data Sheets*, *At. Data Nucl. Data Tables*) all of the work undertaken within the coordinated research project.

[**Sec. note**: On 6 June 2016, Capote reached preliminary agreement with the editor of *Nuclear Data Sheets* (P. Oblozinsky) to publish the monitor reactions paper in January 2018 (decision was confirmed in November 2016, and the paper will be subject to peer-review). Additionally, three other papers will be published in other peer-review journal(s).]

Table 3: Cross-section studies of monitor reactions.

Cross sections	Agreed responsibilities, status and actions
$^{27}Al(p,x)^{22}Na$	The CRP will not recommend data above 100 MeV because the contribution of secondary neutrons to the production is confounding. Use the fit up to 100 MeV, PADE 18 with ~ 6 % uncertainty. Engle will make corrections to the LANL data set for ^{24}Na Gruetter data and re-send to Ignatyuk - completed. *Ignatyuk requests LANL to re-examine $^{27}Al(p,x)^{22}Na$ reaction to attempt to deal with non-physical "bump" near 100 MeV assumed to result from secondary neutron contributions.*
$^{27}Al(p,x)^{24}Na$	The CRP will not recommend data above 100 MeV because the contribution of secondary neutrons to the production is confounding. ^{24}Na needs no corrections; Ignatyuk to use existing file fit to 100 MeV.
$^{27}Al(d,x)^{22,24}Na$	Accept Pade 21 fit for ^{22}Na up to 100 MeV. For ^{24}Na, some points were excluded. Accept Pade 12 fit up to 100 MeV.
$^{27}Al(^{3}He,x)^{22,24}Na$	New experimental data to be provided by Lebeda to Tárkányi by June 2, 2016; Tárkányi to clarify the selected data set.
$^{27}Al(\alpha,x)^{22,24}Na$	Tárkányi to clarify the selected data set and provide data to Ignatyuk by end of June 2016.
$^{nat}Ti(d,x)^{46}Sc$	Accept Pade 13, N=372.
$^{nat}Ti(^{3}He,x)^{48}V$	Lebeda has new measurements on ^{48}V up to 47 MeV. Lebeda to provide data to Ignatyuk and Tárkányi by June 2, 2016 for inclusion. Tárkányi to send to Ignatyuk by end of June 2016.
$^{nat}Ni(d,x)^{56}Co$	CRP will recommend data up to 50 MeV. Accept Pade 11; fit uncertainties to be increased by Ignatyuk to at least 5%.
$^{nat}Ni(d,x)^{58}Co$	Accept Pade 12.
$^{nat}Cu(p,x)^{58}Co$	Lebeda to provide to LANL new absolute measurements up to 36 MeV and Shahid data; Heydegger data to be de-selected by LANL; final data set to be sent to Ignatyuk – completed June 1, 2016. Accept Pade 14cc.
$^{nat}Cu(p,x)^{62}Zn$	Lebeda to provide new absolute measurements up to 36 MeV to Hermanne for inclusion; Hermanne to send new data set to Ignatyuk; new data to be published (e.g. ARRONAX 2016) will be used for validation only.
$^{nat}Cu(p,x)^{63}Zn$	Lebeda to provide new absolute measurements up to 36 MeV to Hermanne for inclusion; Hermanne to correct Hansen data uncertainties plus others and to send new data set to Ignatyuk for re-fit. Pade L18 fit appears good.
$^{nat}Cu(p,x)^{65}Zn$	Lebeda to provide new absolute measurements up to 36 MeV to Hermanne for inclusion; Hermanne to include Shahid data, to check fit and to verify status of Uddin data (recommended to be removed). Accept Pade L13; uncertainties to be increased to 5%.

$^{nat}Cu(d,x)^{62}Zn$	Accept Pade 9.
$^{nat}Cu(d,x)^{63}Zn$	CRP will not recommend due to deviation at 20 MeV and at 45 MeV. However, accept Pade 12.
$^{nat}Cu(d,x)^{65}Zn$	Accept Pade 13C; uncertainties to be increased to 6%.
$^{nat}Cu(\alpha,x)^{66}Ga$	CRP will recommend up to 40 MeV only. Hermanne to re-visit the original assessment with respect to data > 40 MeV and to confirm energy range. New Usman data to be used for validation only. Accept Pade16.
$^{nat}Cu(\alpha,x)^{67}Ga$	New Usman data to be used for validation only. Accept Pade 18; uncertainties to be increased by 4%.
$^{nat}Cu(\alpha,x)^{65}Zn$	New Usman data to be used for validation only. Accept Pade 12; uncertainties to be increased by 4%.
$^{nat}Mo(p,x)^{96m+g}Tc$	Lebeda to include new data (Lebeda and others) and send selected data to Ignatyuk by end of July 2016.
previously recommended data to be re-evaluated	***All monitor reaction cross sections included in IAEA-TECDOC-1211 but not listed above will be re-evaluated by Debrecen/VUB to include uncertainties and covariance.***
$^{nat}Ti(p,x)^{48}V$	Data to be published at higher energies will be included. Lebeda to send data to Hermanne. New evaluation to be completed by end of July, 2016 and will extend up to 100 MeV.
$^{nat}Ti(p,x)^{46}Sc$	Hermanne to add new data (ARRONAX, Lebeda), assess data quality and send selected data set to Ignatyuk by end of July, 2016 for re-fitting.
$^{nat}Ni(p,x)^{57}Ni$	Data selected by Hermanne was re-sent to Ignatyuk for re-fitting.
$^{nat}Cu(p,x)^{56}Co$	LANL to consider new data (LANL, ARRONAX), assess up to 200 MeV, and send selected set to Ignatyuk by end of July 2016.
$^{nat}Ti(d,x)^{48}V$	Accept Pade 18. Recommended data should include a note on potential interference from ^{48}Sc in the period less than 2 weeks post irradiation.
$^{nat}Ni(d,x)^{61}Cu$	Potential systematic shifts due to use of different gamma lines were considered. Accept Pade 10.
$^{nat}Fe(d,x)^{56}Co$	Hermanne to de-select Nakua 2006 data, and re-send to Ignatyuk for re-fitting by July 1, 2016.
$^{nat}Cu(^{3}He,x)^{66}Ga$	Data compiled and assessed. Tárkányi to send to Ignatyuk by July 31, 2016.
$^{nat}Cu(^{3}He,x)^{63}Zn$	Data compiled and assessed. Tárkányi to send to Ignatyuk by July 31, 2016.
$^{nat}Cu(^{3}He,x)^{65}Zn$	Data compiled and assessed. Tárkányi to send to Ignatyuk by July 31, 2016.
$^{nat}Ti(^{3}He,x)^{51}Cr$	Delete from the monitor list.
$^{nat}Ti(\alpha,x)^{51}Cr$	Tárkányi to send selected data set to Ignatyuk by July 31, 2016.

Table 4: Cross-section studies for the production of diagnostic γ emitters.

Cross sections	Agreed responsibilities, status and actions
$^{90}Zr(n,p)^{90m+g}Y$	Completed; results are equivalent to the Dosimetry Library IRDFF; evaluation is available; Capote to provide to Tárkányi and Engle material for publication manuscript.
$^{100}Mo(n,2n)^{99}Mo$	Carlson to provide selected data (up to 20 MeV) and Empire calculation (up to 40 MeV) to Capote and Ignatyuk for fitting; Nagai to provide to Carlson evaluated differential cross sections used to compare with Nagai yield measurements as an independent, parallel validation exercise; Carlson to make comparison.
$^{100}Mo(p,2n)^{99m}Tc$	Selected data provided to Ignatyuk by Lebeda. Suryanarayana to provide additional data points to Capote to be included; Ignatyuk to fit.
$^{100}Mo(p,x)^{99}Mo$	Selected data provided to Ignatyuk by Lebeda. Suryanarayana to provide additional data points to Capote to be included; Ignatyuk to fit.
$^{100}Mo(d,3n)^{99m}Tc$	Selected data provided to Ignatyuk by Tárkányi; Ignatyuk to fit. CRP will not recommend cross sections due to poor quality of measured data.
$^{100}Mo(d,x)^{99}Mo$	Selected data provided to Ignatyuk by Tárkányi; Ignatyuk to fit.
$^{100}Mo(\gamma,n)^{99}Mo$	Capote to review data supplied by Suryanarayana for suitability.
$^{238}U(\gamma,f)^{99}Mo$	Capote to review data supplied by Suryanarayana for suitability.
$^{68}Zn(\gamma,p)^{67}Cu$	Data and analysis will be supplied by Suryanarayana to Capote by end of 2016.
$^{67}Zn(n,p)^{67}Cu$	Completed; results are equivalent to the Dosimetry Library IRDFF; evaluation is available; Capote to provide to Tárkányi and Engle material for publication.
$^{68}Zn(n,x)^{67}Cu$	Nagai to estimate quality of existing data using existing differential measurements, predictions by colleagues, and own yield measurements. Nagai to provide to Capote a plot and tabulated data of excitation function used for yield calculations and contributions from isotopic impurities in the ^{68}Zn target used for experiments. Capote to provide to Tárkányi and Engle data needed for publication.
$^{64}Zn(n,p)^{64}Cu$	Completed; results are equivalent to the Dosimetry Library IRDFF; evaluation is available; Capote to provide to Tárkányi and Engle material for publication.
$^{112}Cd(p,2n)^{111}In$	Accept Pade 9; recommend up 40 MeV.
$^{124}Xe(p,x)^{121}I$	Tárkányi to provide uncertainties to Ignatyuk; fit up to 40 MeV; recommend data up to 35 MeV; complete by July 31, 2016.
$^{124}Xe(p,2n)^{123}Cs$	Tárkányi to provide selected data set to Ignatyuk by July 31, 2016 for fitting.
$^{124}Xe(p,x)^{123}Xe$	Tárkányi to de-select Tárkányi data and to provide selected data set to Ignatyuk by July 31, 2016 for fitting.
reactions leading to ^{51}Cr	Usefulness of ^{51}Cr is unclear. Tárkányi to assess which reactions make sense for production - only these will be included.
$^{nat}V(p,n)^{51}Cr$	Tárkányi to provide selected data set to Ignatyuk for fitting.
$^{nat}V(d,xn)^{51}Cr$	Tárkányi to apply energy shift to Weinreich data, and provide selected set to Ignatyuk for fitting.
$^{nat}Cr(p,x)^{51}Cr$	Note that this reaction is not useful. Remove from CRP. Tárkányi will still provide selected set to Ignatyuk for fitting.
$^{nat}Cr(d,x)^{51}Cr$	Note that this reaction is not useful. Remove from CRP. Tárkányi will still provide selected set to Ignatyuk for fitting.
$^{nat}Ti(\alpha,x)^{51}Cr$	Completed as part of the monitor reaction list.
$^{nat}Ti(^{3}He,x)^{51}Cr$	Note that this reaction is not useful. Remove from CRP. Tárkányi will still provide selected set to Ignatyuk for fitting.
$^{nat}Mn(p,x)^{51}Cr$	Tárkányi to provide selected data set to Ignatyuk for fitting.

$^{nat}Mn(d,x)^{51}Cr$	Note that this reaction is not useful. Remove from CRP. Tárkányi will still provide selected set to Ignatyuk for fitting.
$^{nat}Fe(p,x)^{51}Cr$	Engle sent LANL data to Tárkányi. Tárkányi to provide selected data set to Ignatyuk for fitting.
$^{203}Tl(p,2n)^{202m}Pb$	Tárkányi to provide selected data set to Ignatyuk for fitting.
$^{203}Tl(p,3n)^{201}Pb$	Tárkányi to provide selected data set to Ignatyuk for fitting.
$^{203}Tl(p,4n)^{200}Pb$	Tárkányi to provide selected data set to Ignatyuk for fitting.
$^{nat}W(\alpha,x)^{186,188}Re$	Nothing will be recommended. Remove from CRP.

Table 5: Cross-section studies for the production of positron emitters.

Production of ^{52}Fe	Addressed in Table 6
$^{58}Ni(p,\alpha)^{55}Co$	(previously assigned to Hussain) All reactions previously assigned to Hussain require re-evaluation. Recommended by the CRP to dedicate additional resources to address these reactions in the future.
$^{54}Fe(d,n)^{55}Co$	(previously assigned to Hussain)
$^{56}Fe(p,2n)^{55}Co$	(previously assigned to Hussain) Re-assess.
$^{nat}Fe(p,x)^{55}Co$	(previously assigned to Hussain) Re-assess.
$^{61}Ni(p,n)^{61}Cu$	(previously assigned to Spahn) Capote to contact Jülich to determine path forward. Data remain to be assessed.
$^{nat}Ni(d,x)^{61}Cu$	Addressed as a monitor reaction in Table 3.
$^{64}Zn(p,\alpha)^{61}Cu$	Lebeda to convert and include literature data from ^{nat}Zn, make selection and send to Ignatyuk by July 31, 2016 for fitting.
$^{66}Zn(p,n)^{66}Ga$	(previously assigned to Hussain)
$^{63}Cu(\alpha,n)^{66}Ga$	Transferred to Hermanne; Hermanne to convert and include natural data, make selection and send to Ignatyuk by July 31, 2016 for fitting.
$^{68}Zn(p,n)^{68}Ga$	(previously assigned to Spahn) Capote to contact Jülich to determine path forward. Data remain to be assessed.
$^{65}Cu(\alpha,n)^{68}Ga$	(previously assigned to Spahn) Capote to contact Jülich to determine path forward. Data remain to be assessed. Note natural data could be converted and used.
$^{93}Nb(p,x)^{90}Nb$	(previously assigned to Hussain) Re-assess.
$^{89}Y(\alpha,x)^{90}Nb$	(previously assigned to Hussain) Re-assess.
$^{89}Y(\alpha,x)^{89}Zr$	CRP will not recommend this reaction due to low yields.
$^{nat}Ge(p,xn)^{72}As$	(previously Lahore responsibility) Re-assess. Nortier to send iThemba data to Tárkányi.
$^{75}As(p,3n)^{73}Se$	(previously assigned to Hussain) Re-assess.
$^{72}Ge(\alpha,3n)^{73}Se$	(previously assigned to Hussain) Re-assess.
$^{76}Se(p,n)^{76}Br$	(previously assigned to Hussain) Re-assess.
$^{77}Se(p,2n)^{76}Br$	(previously assigned to Hussain) Re-assess.
$^{75}As(\alpha,3n)^{76}Br$	(previously assigned to Hussain) Re-assess.
$^{86}Sr(p,n)^{86}Y$	(previously assigned to Hussain) Re-assess.
$^{88}Sr(p,3n)^{86}Y$	(previously assigned to Hussain) Re-assess.
$^{85}Rb(\alpha,3n)^{86}Y$	(previously assigned to Hussain) Re-assess.
$^{89}Y(p,n)^{89}Zr$	Completed; Ignatyuk to fit by July 31, 2016.
$^{89}Y(d,2n)^{89}Zr$	Lebeda to include own measurements and to provide selected data set to Ignatyuk by July 31, 2016 for fitting.
$^{94}Mo(p,n)^{94m}Tc$	Lebeda to convert available data on ^{nat}Mo to ^{94}Mo and to send to Carlson. Carlson to re-scale Rösch energy points, and send data set to Ignatyuk by July 31, 2016 for fitting.
$^{92}Mo(\alpha,x)^{94m}Tc$	Data contradictory. Carlson to select Levkovski data, and send selected data set to Ignatyuk by July 31, 2016 for fitting.

$^{110}Cd(p,n)^{110m}In$	Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
$^{110}Cd(d,2n)^{110m}In$	Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
$^{107}Ag(\alpha,n)^{110m}In$	Capote sent Kim data to Tárkányi for inclusion. Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
$^{109}Ag(^{3}He,2n)\ ^{110m}In$	Remove from CRP.
$^{120}Te(p,n)^{120}I$	Accept Pade11.
$^{122}Te(p,3n)^{120}I$	Accept Pade7.

Table 6: Cross-section studies for the production of positron emitters: generators.

Generator	Cross sections	Agreed responsibilities, status and actions
^{62}Zn/^{62}Cu		PET analogue of therapeutic ^{67}Cu.
	^{63}Cu(p,2n)^{62}Zn	Covered as a monitor reaction. Values from the fitted monitor reaction on ^{nat}Cu will be normalized by Tárkányi up to 32 MeV.
	^{63}Cu(d,3n)^{62}Zn	Covered as a monitor reaction. Values from the fitted monitor reaction on ^{nat}Cu will be normalized by Tárkányi up to 34 MeV.
	^{60}Ni(α,2n)^{62}Zn	Remove from CRP.
	^{60}Ni(^{3}He,n)^{62}Zn	Remove from CRP.
^{68}Ge/^{68}Ga		PET analogue of proposed/new therapeutic ^{67}Ga.
	^{nat}Ga(p,xn)^{68}Ge	Accept Pade 9.
	^{69}Ga(p,2n)^{68}Ge	Accept Pade 9.
	^{71}Ga(p,4n)^{68}Ge	Remove from CRP.
^{72}Se/^{72}As	^{75}As(p,4n)^{72}Se	Accept Pade 8; Recommend data only up to 55 MeV.
	^{nat}Br(p,x)^{72}Se	Accept Pade 10cor.
^{82}Sr/^{82}Rb	^{nat}Rb(p,xn)^{82}Sr ^{85}Rb(p,4n)^{82}Sr	Engle to re-adjust cross sections using 15.08(16)% branching ratio for 776-keV gamma ray of ^{82}Rb (ENSDF decay-data evaluation by Tuli). Engle to send data sets to Ignatyuk by July 31, 2016. CRP report should include a clear note that the new branching ratio was adopted. Fits for these two reactions should ensure that the final recommended cross sections reflect and are consistent with the ^{85}Rb abundances in the targets.
^{52}Fe/^{52m}Mn	^{55}Mn(p,4n)^{52}Fe	(previously assigned to Hussain) Re-assess.
	^{nat}Ni(p,x)^{52}Fe	De-select Titarenko data. Accept Pade 6.
	^{52}Cr(^{3}He,3n)^{52}Fe	Remove from CRP (no ^{3}He beams).
	^{50}Cr(α,2n)^{52}Fe	Hermanne to select data up to 40 MeV, and send to Ignatyuk by July 31, 2016 for fitting.
^{110}Sn/^{110m}In		PET analogue of therapeutic ^{111}In and ^{114m}In.
	^{nat}In(p,x)^{110}Sn	Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
	^{nat}Cd(^{3}He,x)^{110}Sn	Remove from CRP.
	^{108}Cd(α,2n)^{110}Sn	Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
^{128}Ba/^{128}Cs		PET analogue of proposed/new therapeutic ^{131}Cs.
	^{133}Cs(p,6n)^{128}Ba	Tárkányi data to be energy shifted. Tárkányi will re-assess and send selected data set to Ignatyuk by July 2016.
^{122}Xe/^{122}I		PET analogue of therapeutic ^{123}I, ^{125}I and ^{131}I.
	^{127}I(p,6n)^{122}Xe	Tárkányi to re-assess and to send data to Ignatyuk by July 31, 2016 for fitting.
	^{127}I(d,7n)^{122}Xe	Remove from CRP.
	^{124}Xe(p,x)^{122}Xe	Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
^{118}Te/^{118}Sb		PET analogue of proposed/new therapeutic ^{117}Sb and ^{119}Sb.
	^{116}Sn(α,2n)^{118}Te	Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
	^{nat}Sb(p,x)^{118}Te	Engle provided new LANL data to Tárkányi; Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.
	^{122}Te(p,x)^{118}Sb	Tárkányi to send data to Ignatyuk by July 31, 2016 for fitting.

$^{140}Nd/^{140}Pr$	$^{141}Pr(p,2n)^{140}Pr$	LANL re-adjusted uncertainties for Hilgers data during third RCM, and re-sent to Ignatyuk for fitting. Provisionally accept Pade 14.
	$^{141}Pr(d,3n)^{140}Nd$	Hermanne to complete compilation and selection of the data and send to Ignatyuk for fitting by Julyi 31, 2016.
	$^{nat}Ce(\alpha,x)^{140}Nd$	No data - remove from CRP.
	$^{nat}Ce(^{3}He,xn)^{140}Nd$	No data - remove from CRP.
$^{44}Ti/^{44}Sc$	Main reactions leading to the parent nucleus	(previously assigned to Spahn) Capote to contact Jülich to determine path forward. Data remain to be assessed. ^{44}Ti half-life evaluation completed by Kondev: $T_{½}$ = (59.1 ± 0.3) y is recommended.

Table 7: Cross-section studies for the production of therapeutic α emitters.

Cross sections	Agreed responsibilities, status and actions
$^{229}Th(\alpha)^{225}Ra(\beta^-)^{225}Ac(\alpha)$ decay chain to ^{213}Bi:	
$^{232}Th(p,x)^{225}Ra$	Engle de-selected Ermolaev data; selection was sent to Ignatyuk. Recommend data up to 200 MeV only due to limitations of relevant production facilities. Use new fit which attempts to evaluate structure at ~ 90 MeV. CRP report to make a strong statement encouraging additional measurements and expressing CRP reservations about the existence of structure in the data.
$^{232}Th(p,x)^{225}Ac$	Engle de-selected Ermolaev data, and sent selected data set to Ignatyuk for fitting up to 200 MeV.
$^{226}Ra(p,2n)^{225}Ac$	CRP to decide on which fit to recommend.
$^{232}Th(p,x)^{227}Ac$	Engle de-selected Ermolaev data, shifted Gauvin data per third RCM discussion, and sent selected data set to Ignatyuk for fitting up to 200 MeV.
$^{230}U(\alpha)^{226}Th(\alpha)$ decay chain:	
$^{231}Pa(d,3n)^{230}U$	Ignatyuk to refit up to 30 MeV based on additional supporting theoretical calculations.
$^{231}Pa(p,2n)^{230}U$	Accept Pade 5 up to 30 MeV as supported by additional theoretical calculations.
$^{232}Th(p,3n)^{230}Pa(\beta^-)^{230}U$	Capote to send data set to Ignatyuk for fitting.
$^{227}Th(\alpha)^{223}Ra(\alpha)$ decay chain	
$^{232}Th(p,x)^{227}Th$	Ermolaev data was de-selected by Ignatyuk. Accept Pade 7; recommend up to 200 MeV only.

Table 8: Cross-section studies for the production of therapeutic electron and X-ray emitters.

Cross sections	Agreed responsibilities, status and actions
^{130}Ba(n,γ)^{131}Ba(EC)^{131}Cs	Evaluation complete.
^{131}Xe(p,n)^{131}Cs	Ignatyuk to truncate excitation function below 5 MeV. Otherwise accept Pade 10.
^{133}Cs(p,3n)^{131}Ba(EC)^{131}Cs	Accept Pade 11.
^{176}Hf(α,2n)^{178}W(EC)^{178}Ta	Tárkányi to send limited data (7 points, rising to 40 MeV) to Ignatyuk by July 31, 2016 for fitting.
^{nat}Ta(p,x)^{178}W	Capote to obtain and provide to Tárkányi the data of Kim. Tárkányi to include these and others, and send selected data set to Ignatyuk by July 2016 for fitting.
^{nat}Ta(d,5n)^{178}W	Tárkányi send selected data set to Ignatyuk by July 2016 for fitting.
^{103}Rh(p,n)^{103}Pd	Reaction evaluation awaits latest decay-data evaluation of the primary gamma and X-ray lines (recommended nuclear decay data were provided by Nichols; calculated atomic decay data to be provided by Kibédi).
^{103}Rh(d,2n)^{103}Pd	Reaction evaluation awaits latest decay-data evaluation of the primary gamma and X-ray lines (recommended nuclear decay data were provided by Nichols; calculated atomic decay data to be provided by Kibédi).

5. Concluding remarks

The contents of this report constitute a summary of the progress made by participants involved in an IAEA coordinated research project dedicated to the derivation of improved cross-section and decay data for radionuclides identified with nuclear medicine, diagnostic procedures and therapeutic applications. Participants reviewed their agreed work as formulated at the second research coordination meeting in December 2014 (IAEA report INDC(NDS)-0675) and undertaken in 2015/16. Both cross-section and decay-data evaluations were discussed in detail. Specific deadlines were set leading up completion of the coordinated research project by the end of 2016. Furthermore, various technical papers will be prepared for submission to specific journals for peer-review and possible publication in 2017. A primary aim at the conclusion of this coordinated research project is to assemble a definitive database dedicated to nuclear medicine for immediate incorporation into the existing user-friendly IAEA-NDS medical portal:

http://www-nds.iaea.org/medportal/

The improved quality of the nuclear data generated during such a series of IAEA-NDS CRPs improves the efficiency of radionuclide production, and enhances nuclide quality through improved purity.

Further responsibilities, continued studies and actions were agreed during the course of the meeting as given in Sections 3 and 4, and detailed within Tables 2 to 8 in terms of assigned responsibilities for data measurements and assessments/evaluations.

Status of ACTIONS from second RCM, 8-12 December 2014

No.	Agreed action		Status
1	**Decay data**: ^{66}Ga: half-life and main γ-ray emission probabilities by the end of January 2015. Decay-data measurements and evaluation in 2015/16.	Kondev	Completed January 2015 – comprehensive evaluation not performed
2	^{111}In/^{111}Cd^{m}: provide Capote with nuclear decay-data evaluation for ^{111}In by the end of March 2015. Benchmark X/Auger study in 2015.	Nichols, Kibédi	Completed mid-2016
3	^{99}Mo/^{99}Tc^{m}: nuclear decay-data evaluation on-going, with completion by the end of March 2015. Subsequent X/Auger study of ^{99}Tc^{m} later in 2015.	Nichols, Kibédi	Completed mid-2016
4	Provide Capote and Tárkányi with nuclear decay-data evaluation for ^{103}Pd by the end of March 2015.	Nichols	Completed March 2015
5	^{103}Pd/^{103}Rh^{m}: X/Auger study in 2015/16.	Kibédi	Completed mid-2016
6	^{125}I: nuclear decay-data evaluation and subsequent X/Auger study in 2015.	Kibédi	Completed mid-2016
7	^{131}Cs: nuclear decay-data evaluation in 2015, and subsequent X/Auger study in 2016.	Nichols, Kibédi	Completed mid-2016
8	^{67}Cu: half-life and main γ-ray emission probabilities by the end of August 2015. Full decay-data evaluation on-going, and subsequent X/Auger study in 2015.	Kondev, Kibédi	Fully completed mid-2016
9	^{52}Mn and ^{52}Mn^{m}: nuclear decay-data evaluations to be completed by mid-Sept 2015.	Luca	Completed mid-2016
10	^{76}Br, ^{120}I: decay-data evaluations in 2015.	Nichols	^{76}Br completed late 2015; **^{120}I on-going – required by end of 2016**
11	^{86}Y: determine timetable for BNL decay measurements, and subsequent availability of data – nuclear decay data evaluation?	Kondev	Report provided - **still on-going**
12	^{178}Ta: nuclear decay-data evaluation for subsequent X/Auger study in 2016.	Kondev, Nichols	**Incomplete – required by end of 2016** **1^{+} low-spin state (FGK);** **7^{-} high-spin state (ALN)**
13	^{230}U decay chain: shared updates and full nuclear decay-data evaluations in 2015/16 as agreed (see also Table 2).	Kellett, Luca	**Partially completed, but still on-going – required by end of 2016**
14	**Cross sections:** Provide the experimental data evaluators with an Excel file with an example ready-to-fit data table to the experimental data evaluators.	Ignatyuk	Completed 2015
15	For other cross-sections actions see Tables 3 to 8.		

ACTIONS from third RCM, 30 May – 3 June 2016

No.	Agreed action		Status
1	**Decay data:** ^{66}Ga: decay-data measurements and evaluation in 2015/16.	Kondev	Still on-going
2	^{86}Y: determine timetable for BNL decay measurements, and subsequent availability of data – nuclear decay data evaluation?	Kondev	Still on-going – maintain communications
3	^{120}I: decay-data evaluations in 2016.	Nichols	Required by end of 2016
4	^{178g,m}Ta: nuclear decay-data evaluations for subsequent X/Auger study in 2016.	Kondev → 1^+ low-spin state; Nichols → 7^- high-spin state	Required before end of 2016
5	^{230}U decay chain: shared updates and full nuclear decay-data evaluations in 2015/16 as agreed.	Kellett, Luca	Required by end of 2016
6	Provide Kondev with their recommended decay data sets in ENSDF format.	Kellett, Luca, Nichols, Kibédi	
7	Process all ENSDF-formatted files from action 6 through new ENSDF drawing package to produce figures of recommended decay schemes.	Kondev	
8	Consider introduction of Auger-electron and X-ray emission uncertainties in decay-data files.	Kibédi	
9	**Cross sections:** New ^{67}Cu decay data – adjust CRP cross-section data on the basis of the newly determined decay data.	Relevant cross-section specialists, Capote (IAEA-NDS medical portal)	On-going
10	New ^{82}Sr decay data – adjust CRP cross-section data on the basis of the newly determined decay data.	Engle, Capote (IAEA-NDS medical portal)	On-going
11	For other cross-section actions see Tables 3 to 8.		
12	**Overall:** Forward any known measurements of Auger-electron and X-ray spectra to Kibédi in order to assist in his validation of the BrIccEmis code (ANU).	All participants	
13	Investigate publishing all CRP-related studies as various papers in public domain journals.	Capote	

APPENDIX 1

Agenda

Third Research Coordination Meeting on
“Nuclear data for charged-particle monitor reactions and medical isotope production”

IAEA Headquarters, Vienna, Austria
30 May – 3 June 2016

Meeting Room MOE03

Monday, 30 May

08:30 – 09:30 **Registration** (IAEA Registration desk, Gate 1)
09:30 – 10:00 **Opening session**
Welcoming address and Introductory Remarks – Meera Venkatesh (Director, NAPC) and Roberto Capote Noy
Election of Chairmen and Rapporteurs
Adoption of Agenda
10:00 – 10:45 **Administrative and financial matters related to participants**

Reaction measurements (RM): A. Hermanne, F. Tarkanyi, O. Lebeda, Y. Nagai, F.M. Nortier, J.W. Engle, S.V. Suryanarayana
Reaction theory and evaluations (EV): B.V. Carlson, A.V. Ignatyuk
Decay Data (DD): F.G. Kondev, A.L. Nichols, M.A. Kellett, T. Kibédi

10:45 – 12:30 **Plenary session 1:** Review and discussion of work done (RM/EV)
12:30 – 14:00 **Lunch**
14:00 – 18:00 **Plenary session 2:** Review and discussion of work done (RM/EV)
(*Coffee break as needed)*

Tuesday, 31 May

09:00 – 12:30 **Plenary session 3:** Review and discussion of work done (RM and DD)
(*Coffee break as needed)*
12:30 – 14:00 **Lunch**
14:00 – 18:00 **Separated groups:** On-going/future work, deliverables, further data needs
(*Coffee break as needed)*
19:00 Dinner at a restaurant

Wednesday, 1 June

09:00 – 12:30 **Separated groups:** On-going/future work, deliverables, further data needs
(*Coffee break as needed)*
12:30 – 14:00 **Lunch**
14:00 – 18:00 **Separated groups:** On-going/future work, deliverables, further data needs
(*Coffee break as needed)*

Thursday, 2 June

09:00 – 12:30 **Separated groups:** On-going/future work, outputs and final publication(s)
(*Coffee break as needed)*

12:30 – 14:00 **Lunch**

14:00 – 18:00 **Separated groups:** On-going/future work, outputs and final publication(s)
(*Coffee break as needed)*

Friday, 3 June

09:00 – 12:30 **Final plenary session: Review and agree main summary points of the meeting**
Review and formalize actions
(*Coffee break as needed)*

12:00 **Closure of the meeting**

12:00 – 13:00 **Lunch**

APPENDIX 2

3rd Research Coordination Meeting on
"Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production"
IAEA, Vienna
30 May – 3 June 2016

LIST OF PARTICIPANTS

AUSTRALIA

Tibor Kibedi
Australian National University
Department of Nuclear Physics
Research School of Physical
Canberra, A.C.T. 260 I
E-mail: tibor.kibedi@anu.edu.au

BELGIUM

Alex Hermanne
Vrije Universiteit Brussels
Cyclotrondepartment
Laarbeeklaan 103 – 1
1090 Brussels
E-mail: aherman@vub.ac.be

BRAZIL

Brett Carlson
Instituto Tecnologico de Aeronautica (ITA)
Praça Mal. Eduardo Gomes, 50
Vila das Acácias
12228-900 Sao Jose dos Campos, SP
E-mail: brett@ita.br

CZECH REPUBLIC

Ondrej Lebeda
Nuclear Physics Institute (NPI)
Czech Academy of Sciences (CAS)
Husinec-Rez, cp. 130
25068 Rez
E-mail: lebeda@ujf.cas.cz

FRANCE

Mark A. Kellett
CEA Centre d'Etudes de Saclay
Laboratoire National Henri Becquerel (LNHB)
Bt 602 – PC 111
91191 Gif sur Yvette Cedex
E-mail: mark.kellett@cea.fr

GERMANY

Ingo Spahn (absent)
Forschungszentrum Jülich Gmbh (FZJ)
PO Box 1913
52425 Jülich
E-mail: i.spahn@fz-juelich.de

HUNGARY

Ferenc Tarkanyi
Hungarian Academy of Sciences
Cyclotron Application Department
Institute for Nuclear Research
Bem ter 18/c, P.O. Box 51
Debrecen 4001
E-mail: tarkanyi@atomki.hu

INDIA

S.V. Suryanarayana
Bhabha Atomic Research Centre (BARC)
Nuclear Physics Division
Trombay
Mumbai, Maharashtra 400 085
E-Mail: suryanarayan7@yahoo.com

JAPAN

Yasuki Nagai
Japan Atomic Energy Agency (JAEA)
Shirakata Shirane 2-4
Tokai-mura, Naka-gun
Ibaraki-ken 319-1195
E-mail: nagai@rcnp.osaka-u.ac.jp

KOREA, Republic of

Guinyun Kim (absent)
Kyungpook National University
1370 Sankyuk-dong, Puk-gu
Daegu 702-701
E-mail: gnkim@knu.ac.kr

PAKISTAN

Mazhar Hussain (absent)
Government College University
Katchery Road
54000 Lahore
E-mail: dr.mazharhussain@gcu.edu.pk

ROMANIA

Aurelian Luca (absent)
National Institute of Physics and Nuclear
Engineering "Horia Hulubei"
Str. Reactorului Nr 30
PO Box MG-6
077125 Maguerele
E-mail: aluca@nipne.ro

RUSSIAN FEDERATION

Anatoly Ignatyuk
Engels Str. 17/15
Obninsk 249032
E-mail: ignatyuk@ippe.ru

UNITED KINGDOM

Alan L. Nichols
38 Mattock Way
Abingdon, OX14 2PQ
E-mail: alanl.nichols@btinternet.com

USA

Meiring Nortier
Los Alamos National Laboratory (LANL)
Chemistry Division
Mail Stop J519
P.O. Box 1663
Los Alamos NM 87545
E-Mail: meiring@lanl.gov

Jonathan W. Engle
Los Alamos National Laboratory (LANL)
P.O. Box 1663
Los Alamos NM 87545
E-Mail: jwengle@lanl.gov

Filip Kondev
Argonne National Laboratory
Nuclear Engineering Division
9700 South Cass Avenue
Argonne IL 60439
E-mail: kondev@anl.gov

IAEA

Roberto Capote Noy
Tel. +43-1-2600 21713
E-mail: r.capotenoy@iaea.org

Arjan Koning
Tel. +43-1-2600 21709
E-mail: a.koning@iaea.org

Both:
IAEA Nuclear Data Section
Vienna International Centre
P.O. Box 100
1400 Vienna, Austria

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

E-mail: nds.contact-point@iaea.org
Fax: (43-1) 26007
Telephone: (43-1) 2600 21725
Web: http://www-nds.iaea.org