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Summary Report

Second Research Coordination Meeting on

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

IAEA Headquarters
Vienna, Austria

8-12 December 2014

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

April 2015

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

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Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna
Austria

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Abstract

A summary is given of the second IAEA research coordination meeting on "Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production". Participants re-assessed and reviewed their on-going commitments and progress with respect to 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. Presentations and discussions are described in this report, along with listings of the progress, current status and plans to ensure completion of the various individual work programmes. All presentations are available on the webpage:
https://www-nds.iaea.org/index-meeting-crp/CHARPAR-2RCM/F41029-2nd-rcm.htm

March 2015

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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 particularly with respect to the efficacious 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 (e.g., half-life, and alpha-particle, electron, positron, gamma-ray and X-ray emission probabilities).

Following on from two earlier Coordinated Research Projects (CRP) on "Charged Particle Cross-Section Database for Medical Radioisotope Production: Diagnostic Radioisotopes and Monitor Reactions" and "Nuclear Data for the Production of Therapeutic Radionuclides"[1,2], the IAEA-NDS has sponsored various consultants' meetings to discuss possible nuclear data requirements up to approximately 2025[3,4,5]. 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 medical radionuclides. The first research coordination meeting was held at IAEA Headquarters from 3 to 7 December 2012 at which agreement was reached concerning a wide range of well-defined work programmes to be implemented by the participants[6].

R.A. Forrest (Section Head, NDS) welcomed the participants. He noted the need for studies to recommend 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 CRP had reached the mid-point, with the aim of producing an appropriate, new database and report by 2017/18. Seventeen CRP participants (B.V. Carlson, J.W. Engle, A. Hermanne, M. Hussain, A.V. Ignatyuk, M.A. Kellett, T. Kibedi, G. Kim, F.G. Kondev, O. Lebeda, A. Luca, T. Nagai, H. Naik, A.L. Nichols, M. Nortier, I. Spahn and F.T. Tárkányi) attended, while the IAEA was represented by R. Capote (Scientific Secretary, Nuclear Data Section) and P. Dimitriou (Nuclear Data Section). F.T. Tárkányi (Institute of Nuclear Research, Hungarian 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

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

[2] "Nuclear Data for the Production of Therapeutic Radionuclides", E. Běták, A.D. Caldeira, R. Capote, B.V. Carlson, H.D. Choi, F.B. Guimarães, A.G. Ignatyuk, S.K. Kim, B. Kiraly, S.F. Kovalev, E. Menapace, A.L. Nichols, M. Nortier, P. Pompeia, S.M. Qaim, B. Scholten, Yu.N. Shubin, J.-Ch. Sublet and F. Tárkányi, **IAEA Technical Reports Series No. 473**, 2011, Editors: S.M. Qaim, F. Tárkányi and R. Capote, International Atomic Energy Agency, Vienna, Austria, ISBN 978-92-0-115010-3.

[3] 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.

[4] 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

[5] 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

[6] 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

and 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 *https://www-nds.iaea.org/index-meeting-crp/CHARPAR-2RCM/F41029-2nd-rcm.htm*. A brief summary of the work scope and status associated with each presentation is outlined below.

2.1 Decay Data

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

An assessment of the ^{44}Ti half-life has been completed, and a value of $T_{1/2}$ = 59.1(3) y recommended on the basis of the ENSDF evaluation by Chen, Singh and Cameron, *Nucl. Data Sheets*, **112** (2011) 2357.

^{67}Cu has the potential for wide application in cancer therapy and SPECT imaging. However, the important decay properties of this radionuclide which impact on the efficacy of any proposed applications arise from only a single measurement that was carried out just over 60 years ago and reported without any uncertainties (Easterday, *Phys. Rev.*, **91** (1953) 653). We have undertaken new γ-ray spectroscopy measurements performed on chemically-purified ^{67}Cu sources produced via the ^{68}Zn(γ,p) reaction (*Appl. Radiat. Isot.*, **70** (2012) 2377). Both singles and βγ-coincidence experiments were carried out with LEPS (γ rays) and PIPS (β^- and CE) detectors. Absolute β^- and γ–ray emission probabilities have been determined, and these were found to differ significantly from currently adopted values. A comprehensive decay-data evaluation of ^{67}Cu has also been initiated, and the experimental results are being prepared for a publication in *Phys. Rev. C*.

New decay spectroscopy studies of ^{66}Ga have begun. The source was produced by means of the ^{66}Zn(p,n) reaction on an enriched, thick target and 12-MeV proton beam. Singles and coincidence measurements have been carried out with the Gammasphere spectrometer, as well as singles measurements with one HPGe detector. The decay scheme of ^{66}Ga is very complex and a significant number of new gamma rays were identified. Data analysis remains in progress.

2.1.2. Decay data evaluations: ^{63}Zn, ^{73}Se, ^{89}Zr, ^{94}Tc^m, ^{99}Mo/^{99}Tc^m, ^{103}Pd/^{103}Rh^m and ^{111}In/^{111}Cd^m, A.L. Nichols (University of Surrey, Guildford, UK)

Agreed assignments: ^{63}Zn, ^{73}Se, ^{89}Zr and ^{94}Tc^m decay-data evaluations completed, approved and placed on the LNHB DDEP web site; ^{76}Br and ^{120}I decay-data evaluations to be undertaken in 2015. Nuclear decay-data evaluations have also been completed for ^{103}Pd/^{103}Rh^m and ^{111}In/^{111}Cd^m, and are on-going for ^{99}Mo/^{99}Tc^m in support of the Auger-electron modelling studies by T. Kibedi and co-workers (Australian National University, Canberra).

^{63}Zn ($T_{½}$ = 38.33(10) min.) decays 100% by electron capture/β^+ decay (Q(EC) = 3366.2 (15) keV) to various excited nuclear levels and the ground state of ^{63}Cu (stable). A reasonably well-defined decay scheme was derived from six sets of gamma-ray measurements, consisting of 20 EC/8 β^+ transitions and 64 gamma-ray emissions, plus two unplaced gamma-ray emissions of low intensity (0.002(1)% and 0.0013(8)%).

^{73}Se ($T_{½}$ = 7.10(9) h) decays 100% by electron capture/β^+ decay (Q(EC) = 2725 (7) keV) to various excited nuclear levels and the ground state of ^{73}As. A reasonably well-defined decay scheme consisting of 16 EC/6 β^+ transitions and 53 gamma-ray emissions was derived from three sets of gamma-ray measurements. An additional eighteen gamma-ray emissions were originally unplaced in the decay scheme − only seven have been incorporated into the decay scheme during the existing study, while the balance of eleven unplaced gamma rays remain in the recommended decay-data file as low-intensity emissions (< 0.065%).

^{89}Zr ($T_{½}$ = 78.42 h) undergoes 100% electron capture/β^+ decay (Q(EC) = 2832.8 (28) keV) to various excited nuclear levels and the ground state of ^{89}Y. A reasonably well-defined decay scheme consisting of five EC transitions, one β^+ emission and five gamma rays was derived from four sets of gamma-ray measurements (no unplaced gamma emissions).

^{94}Tc^{m} ($T_{½}$ = 51.9 min.) undergoes 100% by electron capture/β^+ decay (Q(EC) = 4332 (5) keV) to various excited nuclear levels and the ground state of ^{94}Mo. A reasonably well-defined decay scheme consisting of 16 EC/7 β^+ transitions and 52 gamma-ray emissions was derived from the gamma-ray measurements. While nineteen gamma-ray emissions were originally defined as unplaced in the decay scheme, twelve of these transitions have been successfully incorporated into the proposed decay scheme during the course of the current study, along with identification of the 1022-keV gamma emission. Thus, six of the observed low-intensity gamma rays remain unplaced (all < 0.20%).

^{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). While the full EC decay process consists of four EC transitions and nine gamma-ray emissions to the ground state of ^{103}Rh, the EC-decay scheme is dominated by EC decay directly to the 35.753 keV excited state of ^{103}Rh^{m} and the resulting IT gamma transition to the stable ^{103}Rh ground state. The resulting recommended data set has been forwarded to Kibedi to assist in the ANU Auger-electron studies.

^{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). A simple decay scheme has been derived predominantly from the conversion-electron measurements, consisting of two EC transitions and three gamma-ray emissions to the stable ground state of ^{111}Cd. The resulting recommended data set has been forwarded to Kibedi to assist in the ANU Auger-electron studies.

^{99}Mo/^{99}Tc^{m}: an extremely substantial number of dedicated references have been assembled (~ 140), and a decay-data evaluation is underway. ^{76}Br and ^{120}I: references are in the process of being assembled before undertaking the planned decay-data evaluation in 2015.

A review of the evaluation and recommended decay data for ^{52}Fe EC/β^+ decay to ^{52}Mn^{m} was undertaken in 2013/14. All comments and corrections were considered and adopted by the evaluator (Luca, IFIN-HH, Romania). As suggested during this refereeing process, Luca has also agreed to evaluate the decay-scheme data for the important β^+-emitting ^{52}Mn^{m} and ^{52}Mn daughter radionuclides.

2.1.3. Improved nuclear decay data for emerging medical radioisotopes, A. Luca (National Institute of Physics and Nuclear Engineering Horia Hulubei (IFIN-HH), Romania)

IAEA Research Contract no. 17442/2012

Decay Data Evaluation Project (DDEP) data-handling procedures have been adopted to evaluate and recommend comprehensive decay data for ^{52}Fe. This radionuclide undergoes 100% electron capture/positron decay to excited levels and the ground state of ^{52}Mn, including population of the important $^{52}Mn^m$ isomer with a level energy of 377.7 keV and half-life of 21.1(2) min. The Q_{EC}-value for ^{52}Fe EC decay of 2375(6) keV was obtained from Wang, *et al*., *Chin. Phys*., **C36** (2012) 1603, while level spins, parities and energies were adopted from the most recent mass-chain evaluation published for A = 52 (Junde Huo, *et al*., *Nucl. Data Sheets*, **108** (2007) 773). An evaluated ^{52}Fe half-life of (8.273 ± 0.008) h was also determined. Other major evaluated data included electron-capture transition energies and probabilities, β^+ and gamma-ray energies and emission probabilities, theoretical internal conversion coefficients calculated by the BrIcc program (Kibedi, *et al*., *Nucl. Instrum. Methods Phys. Res.*, **A589** (2008) 202), Auger-electron energies and emission probabilities, conversion electrons, and K and L X-ray energies and emission probabilities. Additional atomic data, such as fluorescence yields, ratios P(KLX)/P(KLL) ratios, P(KXY)/P(KLL), *etc.*, were also evaluated. Huang Xiaolong (China Nuclear Data Center, China Institute of Atomic Energy, Beijing, China) assisted with the provision of several references of significant importance to the satisfactory completion of this particular evaluation. The ^{52}Fe decay-data recommendations were peer-reviewed, and the resulting approved data set has been added to the existing DDEP database.

The consistency analysis for the recommended ^{52}Fe decay data underlined the importance of $^{52}Mn^m$ EC/β^+ decay to ensure complete coverage of the important nuclear parameters required for medical applications. Therefore, work will continue at IFIN-HH with further decay-data evaluations of $^{52}Mn^m$ and ^{52}Mn (deadline of September 2015), followed by previously agreed evaluations of ^{230}U and ^{226}Th (late 2015 and early 2016).

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

As part of the CRP, staff at the French national standards laboratory (Laboratoire National Henri Becquerel (LNHB)) are performing decay scheme evaluations. ^{61}Cu decay data have been evaluated for monitor reactions. An evaluated half-life of 3.366(33) h has been proposed from a set of four discrepant values, using an expanded uncertainty to cover the most accurate experimental value from 1982 - further measurements would be useful. Although establishing the EC-positron branching fraction of ^{61}Cu to the ground state is particularly difficult, a self-consistent decay scheme has been developed and recommended during the course of these studies.

Following a comprehensive evaluation in 2012, the recommended decay scheme of positron-emitting ^{64}Cu has been revisited after some doubt was expressed about the validity of the weak gamma line at 1345.77 keV following activation measurements at Jülich. The intensity of this line was measured by various metrology laboratories during 2012 in the context of a EURAMET project, all yielding consistent values upon which the 2012 evaluation had been based. The current recommendations remain strongly based upon these respected studies.

The ^{230}U decay chain contains a significant number of alpha emitters potentially appropriate for radiotherapeutic applications. Therefore, all radionuclides within this eight-member chain are being evaluated in collaboration with IFIN-HH (see sub-section 2.1.3, above). Decay data for six of the chain are being evaluated and updated by LNHB from ^{222}Ra to ^{210}Po, while IFIN-HH staff address ^{230}U and ^{226}Th. Complete evaluations have been finalised for ^{210}Po and ^{210}Bi, and all others are in progress to become available during 2015.

The evaluated data from LNHB, are undertaken as part of the Decay Data Evaluation Project (DDEP) and the means to access these data were also presented. They include 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 expected for publication in 2015. All recommended decay data are available from the dedicated DDEP website (*http://www.nucleide.org/DDEP_WG/DDEPdata.htm*) where detailed evaluator comments are also stored. Alternatively, a tool for gamma and alpha spectroscopists has been developed at the LNHB, providing a user interface by which the DDEP database can be searched (available at *http://laraweb.free.fr*).

Finally, work is underway to measure and calculate beta spectra. The BETASHAPE code is being developed at LNHB, and has been partially validated against measurements made as part of a PhD thesis (also at LNHB). Further measurements of higher-order beta transitions are planned in order to validate the code further, prior to wider release.

2.1.5 Evaluation of Auger electron yields for medical radioisotopes, T. Kibédi (Australian National University, Canberra, Australia)

The targeting of tumours by Auger electrons has been suggested over many years, see for example Howell (*Med. Phys*., **19** (1992) 1371). Over more recent years, significant progress has been made in understanding the biological effect of low-energy electrons (e.g., Howell, *Int. J. Radiat. Biol*., **84** (2008) 959; Rezaee, *et al*., *Med. Phys*., **41** (2014) 181502), which was essential to the preparation of suitable strategies for clinical trials leading to the first successful phase 1 study of ^{111}In-DTPA-hEGF for the treatment of sixteen breast cancer patients (Vallis, *et al*., *Am. J. Nucl. Med. Mol. Imaging*, **4** (2014) 181).

Accurate knowledge of the full energy spectrum of the Auger electrons is a crucial first step in the development of feasible cancer treatment strategies. Unfortunately, the Auger-electron rates of the most commonly used radioisotopes (^{99}Tc^{m}, ^{111}In, ^{125}I, etc.) vary rather significantly, and are judged to be inadequately defined. Decay-data assessments indicate that uncertainties in such data arise from a lack of accurate nuclear structure and atomic data. More specifically, the contributions of the M, N, O, etc. atomic shells have been ignored in a number of cases, even though the energies of the Auger electrons associated with these shells are particularly important for medical applications.

A new physical model is being developed by Lee, *et al*., (*Comput. Math. Methods Med.*, 2012, Article ID 651475) which takes the most recent nuclear structure information, internal conversion coefficients and electron capture rates to calculate the initial distribution of electron vacancies. Atomic transition energies are calculated using the RAINE code (Band, *et al*., *At. Data Nucl. Data Tables*, **81** (2002) 1) and the rates are taken from the EADL database (Perkins, *et al*., Lawrence-Livermore National Laboratory report, **30** (1991)). The propagation of vacancies is handled by means of the

Monte-Carlo technique. Results from the new model have been tested with a number of radioisotopes, and compared with available experimental data and existing calculations. We are currently developing new calculational procedures in order to overcome limitations in the EADL database – these studies involve the Grasp2K (Jönsson, *et al*., *Comput. Phys. Commun*., **184** (2013) 2197) and RATIP (Fritzsche, *Comput. Phys. Commun*., **183** (2012) 1525) programs, undertaken in collaboration with P. Jönsson and J. Ekeman (University of Malmö, Sweden) and J. Marques (University of Lisbon, Portugal). Other co-workers are B.Q. Lee and A.E. Stuchbery (RSPE, ANU, Australia), F.G. Kondev (Argonne National Laboratory, USA) and A.L. Nichols (University of Surrey, UK).

2.2 Reaction Cross Sections

2.2.1. Cross-section studies at Vrije Universiteit Brussels (VUB), A. Hermanne (Vrije Universiteit, Brussels, Belgium)

At the first RCM in December 2012, tasks identified with monitor reactions for deuteron and proton beams and the production of two diagnostic radionuclides were allocated to the VUB, mostly in collaboration with the ATOMKI group. Results were briefly presented and, more specifically, the content and structure of the data files sent between October 2013 and January 2014 to Ignatyuk, with copies to Capote and Tárkányi, were discussed. Data sets for the requested six proton monitoring reactions (Ti(p,x)^{48}V, Ni(p,x)^{57}Ni, Ti(p,x)^{46}Sc, Cu(p,x)^{62,63,65}Zn) and eleven deuteron monitoring reactions (Ti(d,x)^{46}Sc, Cu(d,x)^{62,63,65}Zn, Al(d,x)^{22,24}Na, Ni(d,x)^{56,58}Co, Ni(d,x)^{61}Cu, Ti(d,x)^{48}V, Fe(d,x)^{56}Co) were obtained from the medical portal of the IAEA, an additional literature search, results obtained in earlier and more recent dedicated experiments performed by the ATOMKI-VUB group (independent measurements and monitoring).

The files for all the reactions considered contain:

- a worksheet with the data sets which contains the uncertainties in the cross sections (overall, beam current, targets thickness, statistics, detector efficiency, and nuclear data), as either taken from the original publication, or estimated/adapted by the compiler;
- an overview of the nuclear data used, and indication of required corrections;
- graphs of all data and selected data, with reasons for deselection.

The same information and structure were adopted for the data files of the medically important radionuclides obtained through the ^{112}Cd(p,2n)^{111}In and ^{nat}Ga(p,x)^{68}Ge-^{68}Ga, ^{69}Ga(p,2n)^{68}Ge-^{68}Ga reactions. Full discussions of the yields and production characteristics for these reactions were published in Adam-Rebeles *et al*. (^{68}Ge/^{68}Ga) *Radiochim. Acta* 101 (2013) 481-489 and Hermanne *et al*. (^{111}In) *Radiochim. Acta* 102 (2014) 1111-1126.

The data will be submitted to Ignatyuk in the form of a single table of selected data, with an overall, realistic uncertainty assigned to each data point. Although published datasets should either be selected or deselected as a whole, obvious single outliers can be removed by the compilers. Ignatyuk has also requested that correlations between datasets (especially from a same laboratory) should be noted and defined. This work is on-going for all 17 datasets, in parallel with inclusion of additional data provided during and shortly after the meeting by participants or recently found in the literature. The files for the deuteron monitors will be forwarded by 15 January 2015, and proton monitors and diagnostic radionuclides by 15 February 2015.

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

The agreed programme of the ATOMKI Nuclear Reaction Data Group consists of measurements and compilation of charged-particle induced reaction data as listed in IAEA report INDC(NDS)-0630. All reactions assigned to ATOMKI have been measured (see Table 1) over the course of 2013/14, and most of the results have been published in journals/conference proceedings (19 publications) or are approved for publication. Nuclear data compiled and submitted by ATOMKI staff are collected together in Table 2, along with a list of the reactions for which data compilations have begun.

There are two important problems related to the compilations and evaluations:

- the number of the reactions dedicated to our group is so large as to require a reduction and neglect of unimportant reactions;
- on the basis of the available material in the literature, all the necessary input information to derive proper covariance matrices has proved either difficult or impossible to prepare; a guide with example cases should be provided to assist all compilers (which will probably necessitate the resubmission of the existing compilations).

Table 1. New experimental cross-section data for monitor and medical radioisotope reactions falling within the responsibility of ATOMKI staff - new measurements and earlier unevaluated irradiations.

Monitor reactions				Diagnostic and therapeutic medical radioisotopes (gamma and positron emitters)			
Target	**Particle**	**E_{in} (MeV)**	**Products**	**Target**	**Particle**	**E_{in} (MeV)**	**Products**
Al	p	65	^{22,24}Na	^{112}Cd	p	65	^{111}In, ^{110m}In
Al	d	50	^{22,24}Na	^{nat}Ni	p	65	^{55}Co
Ti	p	36	^{48}V, ^{46}Sc	^{nat}Ni	d	50	^{55}Co
Ti	d	21	^{48}V, ^{46}Sc	^{nat}Ge	p	65	^{72}As
Fe	p	32.5	^{55,56,57}Co	^{nat}Se	p	36	^{76}Br
Fe	d	21	^{56,57,58}Co	^{nat}Ga	p	65	^{68}Ge/^{68}Ga
Ni	p	65	^{56,57,58}Co, ^{56}Ni	^{nat}Tl	p	36	^{201}Tl
Ni	d	50	^{56,57,58}Co	^{124}Xe	p	36	^{123}Cs, ^{123}Xe, ^{121}I
Cu	p	65	^{62,63,65}Zn, ^{56,57,58}Co, ^{61}Cu	^{nat}Hf	α	40	^{178}W/^{178}Ta
Cu	d	50	^{62,63,65}Zn, ^{58}Co	^{nat}Ta	d	40	^{178}W/^{178}Ta
				^{nat}Ag	α	40	^{110m}In
				^{nat}Ag	^{3}He	26	^{110m}In
				^{nat}In	p	65, 70	^{110}Sn/^{110m}In
				^{nat}Cr	α	40	^{52}Fe
				^{nat}Cd	^{3}He	26	^{110}Sn/^{110m}In

Table 2. Status of ATOMKI compilations and evaluations of cross sections.

Submitted: Monitor reactions	
^{3}He monitors	^{27}Al(^{3}He,x)^{22}Na ^{27}Al(^{3}He,x)^{24}Na
α-particle monitors	^{27}Al(α,x)^{22}Na ^{27}Al(α,x)^{24}Na
p-monitors	^{nat}Mo(p,x)^{96}Tc
Gamma emitters	
^{123}I	^{124}Xe(p,2n)^{123}Cs ^{124}Xe(p,pn)^{123}Cs ^{124}Xe(p,x)^{121}I
^{201}Tl	^{203}Tl(p,2n)^{202}Pb ^{203}Tl(p,3n)^{201}Pb ^{203}Tl(p,4n)^{200}Pb
^{51}Cr	^{nat}Ti(α,xn)^{51}Cr ^{51}V(p,n)^{51}Cr ^{51}V(d,2n)^{51}Cr
Positron emitters	
^{122}Xe-^{122}I	^{127}I(p,6n)^{122}Xe ^{127}I(p,7n)^{122}Xe ^{124}Xe(p,x)^{122}Xe
^{62}Zn-^{62}Cu	^{63}Cu(p,2n)^{62}Zn ^{63}Cu(d,3n)^{62}Zn ^{60}Ni(α,2n)^{62}Zn ^{60}Ni(^{3}He,n)^{62}Zn
Therapeutic radioisotopes	
^{131}Cs	^{131}Xe(p,n)^{131}Cs ^{133}Cs(p,3n)^{131}Ba-^{131}Cs

In progress: Positron emitters	
^{110m}In	Ag+α → ^{110m}In, ^{110g}In Ag+^{3}He → ^{110m}In, ^{110g}In Cd+p → ^{110m}In, ^{110g}In Cd+d → ^{110m}In, ^{110g}In
^{110}Sn-^{110m}In	In+p → ^{110}Sn/^{110m}In Cd+^{3}He → ^{110}Sn/^{110m}In Cd+α → ^{110}Sn/^{110m}In
^{52}Fe-^{52}Mn	Cr+α → ^{52}Fe Cr+^{3}He → ^{52}Fe Ni+p → ^{52}Fe
^{118}Te-^{118}Sb	Te+p → ^{118}Te Sb+p → ^{118}Te Sn+α → ^{118}Te
^{178}W-^{178}Ta	^{181}Ta(p,4n) → ^{178}W ^{181}Ta(d,5n) → ^{178}W ^{176,177,178}Hf(α,xn) → ^{178}W ^{176,177}Hf(^{3}He,xn) → ^{178}W
Additional monitor reactions	
^{3}He monitors	^{nat}Ti(^{3}He,x)^{51}Cr ^{nat}Cu(^{3}He,x)^{66}Ga, ^{63,65}Zn
p monitors	^{197}Au(p,x)^{197m,195m193m}Hg, ^{194,196}Au

2.2.3. Assessment of nuclear reaction cross-section data, M. Hussain (Government College University, Lahore, Pakistan)

Over the previous two years, an extensive literature survey has been undertaken in order to analyse the production cross-section data of positron emitters, as assigned to Lahore. Assessments for the production cross sections of the following radionuclides were completed:

^{55}Co – reactions ^{58}Ni(p,α)^{55}Co, ^{54}Fe(d,n)^{55}Co, ^{56}Fe(p,2n)^{55}Co, ^{nat}Fe(p,x)^{55}Co;
^{66}Ga – reactions ^{66}Zn(p,n)^{66}Ga, ^{63}Cu(α,n)^{66}Ga;
^{73}Sc – reactions ^{75}As(p,3n)^{73}Se, ^{72}Ge(α,3n)^{73}Se;
^{76}Br – reactions ^{76}Se(p,n)^{76}Br, ^{77}Se(p,2n)^{76}Br,^{75}As(α,3n)^{76}Br;
^{86}Y – reactions ^{86}Sr(p,n)^{86}Y, ^{88}Sr(p,3n)^{86}Y, ^{85}Rb(α,3n)^{86}Y.

Other assessment work in progress:

^{52}Fe – reactions ^{55}Mn(p,4n)^{52}Fe, ^{nat}Ni(p,x)^{52}Fe, ^{52}Cr(^{3}He,3n)^{52}Fe;
^{72}As – reactions ^{nat}Ge(p,xn)^{72}As;
^{90}Nb – reactions ^{93}Nb(p,x)^{90}Nb, ^{89}Y(α,x)^{90}Nb;
^{120}I – reactions ^{120}Te(p,n)^{120}I, ^{122}Te(p,3n)^{120}I.

All of these assessments will be completed by the end of 2015.

2.2.4. Work undertaken at NPI, O. Lebeda (Nuclear Physics Institute, Rez, Czech Republic)

The following work has been performed:

a). New data for the $^{nat}Ti(^{3}He,x)^{48}V$ monitoring reaction – cumulative cross-sections were measured in the range 6.5–47 MeV. The cross-sections will be compared with the three existing data sets, and supplied to Ignatyuk to determine recommended cross-sections.

b). New data for the $^{89}Y(d,x)$ reactions with particular focus on $^{89}Y(d,2n)^{89m}Zr$, $^{89}Y(d,2n)^{89}Zr$ and $^{89}Y(d,2n)^{89m+g}Zr$ were measured in the energy range of 4–20 MeV. These resulting evaluated data will be compared with published cross-sections, and all available data for $^{89}Y(d,2n)^{89m+g}Zr$ will be assessed and forwarded to Ignatyuk for calculation of a final set of recommended cross-sections. Comparison of the monitoring $^{nat}Ti(d,x)^{48}V$ and $^{27}Al(d,x)^{24}Na$ reactions show that the recommended cross-sections for both reactions differ – the latter gives a beam current value ca 13% higher than the former (while the former is very close to the collected total beam charge deposited on the target).

c). New data for the $^{75}As(p,x)$ reactions with particular focus on $^{75}As(p,3n)^{73}Se$ have been measured in the energy range of 18.6–36.2 MeV. These data will be evaluated after separate determinations of the thickness of each As target layer. As demonstrated before, the $^{nat}Ti(p,x)^{48}V$ monitoring reaction exhibits a more gradual decrease than suggested by the IAEA-recommended cross-sections. New data for monitoring reactions on copper have also been obtained (Cu used as a support to other targets) to be compared with published cross-sections. All published data for $^{75}As(p,3n)^{73}Se$ will be assessed, and sent to Ignatyuk for calculation of the final recommended cross-sections.

d). Published data have been assembled for the $^{nat}Mo(p,x)^{96m+g}Tc$ monitoring reaction and the $^{100}Mo(p,2n)^{99m}Tc$ and $^{100}Mo(p,x)^{99}Mo$ reactions (also available from the measurements on natural molybdenum). Our new data set for these systems will be available in the first half of 2015, when all available data will be assessed in consultation with Tárkányi. Selected data sets will be passed to Ignatyuk for calculation of the final recommended cross-sections.

2.2.5. Measurements of charged-particle induced reactions, Guinyun Kim (Kyungpook National University, Republic of Korea)

The MC-50 cyclotron facility at the Korea Institute of Radiological and Medical Science (KIRAMS) has been used to measure the excitation functions for proton-induced reactions of ^{nat}Fe, ^{nat}Nb, ^{nat}Cu and ^{nat}Hf and alpha-induced reactions of ^{89}Y, ^{nat}Al, ^{nat}Cu and ^{nat}W up to an incident beam energy of 45 MeV by means of the stacked-foil technique combined with high-resolution γ-ray spectroscopy. Comparisons were also made with existing experimental data in the EXFOR data library and theoretical calculations as available in the TENDL library (data available online at ftp://ftp.nrg.eu/pub/www/talys/tendl2013/tendl2013.html).

a). Cross section measurements of monitor reactions:
Excitation functions have been measured for the monitor reactions of $^{nat}Cu(p,x)^{62,65}Zn$, $^{nat}Cu(p,x)^{58}Co$ [1], and $^{27}Al(p,x)^{22,24}Na$ [2] over the energy range of their threshold to 45 MeV by means of the stacked-foil activation and off-line

γ-ray technique. Furthermore, excitation functions of the monitor reactions of $^{nat}Cu(\alpha,x)^{66,67}Ga$, ^{65}Zn were measured over the energy range 15-42 MeV, and will be submitted for publication.

b). Cross section measurements of diagnostic γ-emitter reactions:
Excitation functions of various reaction products such as $^{55,56,57}Co$, ^{52}Fe, $^{52,54}Mn$ and ^{51}Cr from the $^{nat}Fe(p,x)$ reactions were measured in the proton energy range between their respective reaction thresholds and 45 MeV [3]. ^{51}Cr is used as a diagnostic γ emitter. Furthermore, measurements were made of the excitation functions of the $^{nat}W(\alpha,x)^{186,188}Re$ reactions by means of a 45-MeV alpha beam. Excitation functions were also determined for the production of $^{181,182m,182g,183,184g,186}Re$ radioisotopes by 45-MeV protons [4].

c). Cross section measurements of positron-emitter reactions:
Production cross sections of ^{55}Co from the $^{nat}Fe(p,x)$ [3] and $^{nat}Ni(p,x)$ reactions have been measured up to a proton-beam energy of 40 MeV by the stacked-foil activation technique [5]. Similar studies have also been performed to determine the production cross sections of ^{90}Nb from the $^{93}Nb(p,x)$ [6] and $^{89}Y(\alpha,x)$ [7] reactions. Cross sections for the $^{89}Y(\alpha,x)^{89}Zr$ reactions were found to be very low.

Cross sections have been measured for the $^{nat}Hf(p,x)$ [8] and $^{nat}Cd(\alpha,x)$ [9] reactions.

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2.2.6. Determination of production cross sections at Forschungszentrum Jülich, I. Spahn (Institute für Nuklearchemie, Jülich, Germany)

Agreed, specific CRP responsibilities for the following charged-particle reactions:

^{61}Cu – reaction $^{61}Ni(p,n)^{61}Cu$;
^{68}Ga – reactions $^{68}Zn(p,n)^{68}Ga$, $^{65}Cu(\alpha,n)^{68}Ga$;
^{72}As – reaction $^{nat}Ge(p,xn)^{72}As$;
^{76}Br – reactions $^{76}Se(p,n)^{76}Br$, $^{77}Se(p,2n)^{76}Br$;
$^{44}Ti/^{44}Sc^{m+g}$.

Other completed and existing studies of relevance:

^{46}Sc – reactions $^{nat}Ti(d,x)^{46}Sc$;
^{48}V – reaction $^{nat}Ti(d,x)^{48}V$;
^{61}Cu – reaction $^{63}Cu(p,x)^{61}Cu$;
$^{65}Cu(\alpha,n)^{66,67}Ga$;
$^{nat}Se(d,xn)^{75,76,77,82}Br$.

Excitation functions for a series of nuclear reactions have been determined by means of the BC-1710 baby cyclotron (17-MeV H^+ and 8- to 10-MeV $^2H^+$) and the JULIC injector for COSY (45-MeV H^+ and 76-MeV $^2H^+$). Alternative production routes, cross sections and potential impurities related to the $^{44}Ti/^{44}Sc^{m+g}$ generator have been assessed, and the needs for additional measurements and subsequent evaluation demonstrated – $^{nat}Sc(p,pn)^{44}Sc^{g}$; ^{45}Ti production via the $^{45}Sc(p,n)$ reaction; ^{43}Sc production via the $^{45}Sc(p,p2n)$ reaction; $^{nat}Ca(p,x)^{44}Sc^{g}$, $^{nat}Ca(p,x)^{44}Sc^{m}$, and $^{nat}Ca(p,x)^{44}Sc^{m+g}$ reactions; $^{nat}Ca(\alpha,x)^{44}Sc^{m+g}$ reactions; comparison of $^{44}Sc^{m}/^{44}Sc^{g}$ ratios as a function of production route.

Both ^{75}Br and ^{76}Br are being considered for PET, while ^{77}Br and $^{80}Br^{m}$ possess the potential for SPECT and Auger therapy. Therefore, assessments have been made of a range of reasonably well-defined cross sections for the $^{nat}Se(d,xn)^{75,76,77,82}Br$ reactions. Measurements have also been carried out on the $^{nat}Ti(d,x)^{44m,46,47,48}Sc$, $^{nat}Ti(d,x)^{48}V$, $^{65}Cu(\alpha,n)^{68}Ga$, and $^{nat}Cu(p,x)^{61}Cu$ reactions.

Cross-section studies planned for 2015 include the $^{61}Ni(p,n)^{61}Cu$, $^{nat}Ge(p,xn)^{72}As$, $^{76}Se(p,n)^{76}Br$ and $^{77}Se(p,2n)^{76}Br$ reactions. The new IBA cyclone 30XP with improved irradiation capabilities will also replace the baby cyclotron in the near future.

2.2.7. Nuclear Data for medical radionuclide production by accelerator neutrons, Y. Nagai (JAEA, Japan)

We have proposed a new route for the production of ^{99}Mo via the $^{100}Mo(n,2n)^{99}Mo$ reaction. Neutrons generated by means of the $^{nat}C(d,n)$ reaction and a 40-MeV, 2-mA deuteron beam irradiate a metallic sample of enriched ^{100}Mo (251 g). Such a combination is estimated to yield 2.7 TBq of ^{99}Mo after two days irradiation. We have also proposed the production of ^{90}Y by the $^{90}Zr(n,p)$ reaction, ^{64}Cu by the $^{64}Zn(n,p)$ reaction, and ^{67}Cu by the $^{68}Zr(n,x)$ reaction – the intensity of the neutron beam with energies from ~10 to 18 MeV is a key issue to achieving sufficient yield of these particular radioisotopes. Neutrons obtained by the $^{nat}C(d,n)$ reaction by means of a 40-MeV deuteron beam have continuous energy spectra with a most probable energy of 14 MeV. Experiments have been carried out to determine the radionuclidic purity and production yields of ^{99}Mo, ^{90}Y, ^{64}Cu and ^{67}Cu by means of the reactions mentioned above, with neutrons generated at the JAEA Takasaki Ion Accelerator facilities for Advanced Radiation Application. The cross-section studies for ^{67}Cu have been published, while data analyses of the remaining measurements are in progress.

Cross sections for the $^{64}Zn(n,p)^{64}Cu$ and $^{67}Zn(n,p)^{67}Cu$ reactions have been determined at E_n=14.7 MeV, whereby the neutrons were produced via the $^{3}H(d,n)^{4}He$ reaction. Measurements were also made of the cross section for $^{nat}Zn(n,x)Cu$, and assessed in conjunction with reported cross sections for the $^{68}Zn(n,x)^{67}Cu$ reaction which differ by a factor of 3.7. A precise value for the cross section of the $^{68}Zn(n,x)^{67}Cu$ reaction was deemed necessary in order to estimate the yield of ^{67}Cu properly (neutrons generated from the $^{nat}C(d,n)$ reaction were used in these specific studies).

An assessment of the cross-section data for the $^{130}Ba(n,\gamma)^{131}Ba$ reaction is in progress, which is relevant to the production of ^{131}Cs.

2.2.8. Evaluation of cross sections for monitor and production reactions, J.W. Engle and F.M. Nortier (Los Alamos National Laboratory (LANL), USA)

The LANL group has 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. A methodology for the evaluation of experimental nuclear cross sections, agreed upon at the previous Research Coordination Meeting, was followed. This effort includes thorough literature searches, review of more than 120 papers, compilation of almost 2000 data points, clear understanding of the experimental approach and details of each measurement, critical evaluation of the experimental methods, implementation of data adjustments where required, and deselection of data in unavoidable cases.

All compilations including the review and capture of experimental details have been completed. The critical evaluation of experimental methods, data adjustment and deselection processes are in progress, and will be completed in time to submit all the data files by March 2015. Accelerator beam time was secured at the LANSCE LINAC for the measurement of ^{nat}Cu(p,x)^{58}Co cross sections up to 100 MeV, and one stacked foil irradiation was performed. Repetitive counting and data analysis are in progress.

The evaluation of the ^{27}Al(p,x)^{24}Na monitor reaction showed that the shape of the excitation function at proton energies above 200 MeV deviates significantly from predictions by accepted high energy codes. Since this reaction is almost exclusively used as a proton-fluence monitor for cross-section measurements at high energies, the discrepancy between theory and experiment was discussed by meeting participants. Agreement was reached that significant contribution by secondary neutrons cannot be ruled out. Use of this reaction at high energies should therefore be discouraged, and a monitor reaction of (p.xn) type in which secondary neutron contributions will not lead to erroneous fluence values (e.g. ^{nat}Ti(p,xn)^{48}V) should be evaluated and recommended instead. The LANL group had also been asked by the U.S. National Isotope Development Center to propose that the intensity for the 776-keV gamma ray emitted in the EC/β^+ decay of ^{82}Rb be evaluated within the CRP, and that a recommended value be published. This gamma is used by the international community to quantify large-scale production batches of ^{82}Sr, and different published intensity values are being applied.

2.2.9. Photon-, neutron- and proton-induced reactions to produce medical isotopes, H. Naik (Bhabha Atomic Research Centre, India)

Various measurements have been made to determine the yields of ^{99}Mo generated from the ^{nat}Mo(γ,n) and ^{238}U(γ,f) reactions at end-point bremsstrahlung energies of 10-16 and 8-17 MeV, respectively. The electron linac at EBC, Kharghar, Navi-Mumbai, India, with an end-point bremsstrahlung energy of 10 MeV and the ELBE facility at Dresden, Germany, operating at bremsstrahlung energies of 12, 14 and 16 MeV, were used to produce ^{99}Mo activity from the ^{nat}Mo(γ,n) reaction. Studies of ^{99}Mo via the ^{238}U(γ,f) reaction have been carried out by means of the Microtron, Mangalgangotri University, Mangalore, Karnataka, India, at an end-point bremsstrahlung energy of 8 MeV, and with the electron linac at EBC, Kharghar, Navi-Mumbai, India, with an end-point bremsstrahlung energy of 10 MeV. Production of ^{99}Mo from the ^{238}U(γ,f) reaction has also been carried out by means of the SAPHIR facility of CEA, Saclay, France, with end-point bremsstrahlung energies of 11.5, 13.4, 15.0 and 17.3 MeV. Off-line γ-ray spectroscopy was used to measure the ^{99}Mo activity of the irradiated samples of ^{nat}Mo and ^{238}U in terms of the 140.9- and 739.5-keV photopeaks. The amounts of ^{99}Mo produced per gram of the ^{nat}Mo and ^{nat}U samples at different end-point bremsstrahlung energies are shown in Table 3.

Table 3. Review of ^{99}Mo production from $^{nat}Mo(\gamma,n)$ and $^{nat}U(\gamma,f)$ by bremsstrahlung irradiation.

Experimental studies	End-point bremsstrahlung energy (MeV)	Activity of ^{99}Mo (μCi) from $^{nat}U(\gamma,f)$ reaction per g for 24 h irradiation	Activity of ^{99}Mo (μCi) from $^{nat}Mo(\gamma,n)$ reaction per g for 24 h irradiation
Microtron (Mangalore, India)	8.0	0.0255 ± 0.0013	--
EBC (Kharghar, India)	10.0	0.309 ± 0.050	0.318 ± 0.048
SAPHIR (CEA, France)	11.5	0.369 ± 0.013	–
ELBE (Dresden, Germany)	12.0	--	0.183 ± 0.001
SAPHIR (CEA, France)	13.4	0.452 ± 0.021	--
ELBE (Dresden, Germany)	14.0	--	0.823 ± 0.073
SAPHIR (CEA, France)	15.0	0.545 ± 0.027	--
ELBE (Dresden, Germany)	16.0	--	4.292 ± 0.288
SAPHIR (CEA, France)	17.3	0.735 ± 0.011	--

^{99m}Tc produced as the decay product of ^{99}Mo from the $^{nat}Mo(\gamma,n)$ reaction at end-point bremsstrahlung energies of 10 MeV has undergone subsequent processing to examine the feasibility of radiochemical separation. Cross sections for the $^{nat}Mo(\gamma,n)^{99}Mo$ reactions at end-point bremsstrahlung energies of 12, 14, 16, 45, 50, 55, 60 and 70 MeV have also been determined, and these data will be communicated at a later date.

Cross-section studies of medical radioisotopes from the $^{238}U(\gamma,f)^{99}Mo$, $^{47}Ti(n,p)^{47}Sc$ and $^{68}Zn(p,n)^{68}Ga$ reactions remain to be fully undertaken and completed. While experimental measurements on the $^{238}U(\gamma,f)^{99}Mo$ reaction have been performed, work on both the $^{47}Ti(n,p)^{47}Sc$ and $^{68}Zn(p,n)^{68}Ga$ reactions has yet to begin.

2.2.10. Several neutron-, proton- and deuteron-induced reactions, B.V. Carlson (Instituto Tecnológico de Aeronáutica, Brazil)

Effort has concentrated on further development of the exclusive DDHMS pre-equilibrium module for the EMPIRE-II code system, a study of the pre-equilibrium emission of complex fragments, development of the tools necessary to evaluate the elastic and inelastic contributions to deuteron-induced reactions, and (as agreed at the first RCM) an initial study of the n, p and d + ^{100}Mo reactions, and preliminary assessments of the $^{64}Zn(n,p)^{64}Cu$, $^{67}Zn(n,p)^{67}Cu$, $^{68}Zn(n,x)^{67}Cu$ as well as the $^{90}Zr(n,p)^{90}Y^{g+m}$ reactions.

Theoretical aspects of the work have progressed reasonably well. The microscopic description of elastic and inelastic deuteron breakup and subsequent compound emission has been introduced into EMPIRE-II, while stripping reactions are in the process of being implemented. However, reaction assessments have languished, with those that have been performed so far restricted to EXFOR data alone. Arbitrary but unjustified renormalization of several of the $^{99}Mo(p,2n)^{100}Tc^m$ data sets showed them to be consistent among themselves and with theoretical calculations performed with EMPIRE-II. A similar consistency was observed when the same form of renormalization was applied to several of the $^{100}Mo(p,x)^{99}Mo$ data sets, although discrepancies with theoretical calculations were apparent at both low and high energies due to the lack of the deuteron pickup mechanism in the calculation.

The inclusion of deuteron stripping reactions in EMPIRE-II should be completed by the end of December 2014. Selected cross sections promised to Nagai by the end of

February 2015 will be prepared and/or calculated next. A more complete assessment of the n, p and d + ^{100}Mo reactions, the $^{64}Zn(n,p)^{64}Cu$, $^{67}Zn(n,p)^{67}Cu$, $^{68}Zn(n,x)^{67}Cu$ and $^{90}Zr(n,p)^{90}Y^{g+m}$ reactions will be undertaken, as well as the $^{89}Y(p,n)^{89}Zr$, $^{94}Mo(p,n)^{94}Tc^{m}$ and $^{92}Mo(a,x)^{94}Tc^{m}$ reactions, which were erroneously not included in our original list of responsibilities. Hopefully, all of these assessments will be ready by the end of June 2015, as promised. After completing this work, we plan to return to theoretical aspects of the project involved with EMPIRE-II, including the effects of pre-equilibrium emission in the decay following inelastic deuteron breakup, as well as the direct (n,d) and (p,d) pickup mechanisms.

2.2.11. Uncertainties and covariances for recommended cross sections, A.V. Ignatyuk (Institute of Physics and Power Engineering (IPPE), Obninsk, Russia)

The unrecognized error-estimation method developed at IPPE can be used to evaluate and derive reasonable uncertainties and covariances for recommended cross sections, and is in the process of being applied to the experimental data generated and provided by the on-going CRP. Analyses of the proton and deuteron monitor reactions have been performed on the basis of the unrecognized error-estimation method (UNERES). Along with consistent consideration of the statistical errors of experimental data, this method determines some systematic data uncertainties that are usually underestimated by their authors and also establishes some implicit correlations of the data.

The UNERES method is based on the assumption that all available experimental data are equally reliable (*prior* assumption), excluding proven erroneous results. Systematic and statistical uncertainties of each experimental study are determined in accordance with the observed data distribution. An initial description of the data is required, and deviations can be considered as the selective values of uncertainties. The average deviation of the experimental data from the approximating function is regarded as the systematic error for each study analyzed, and the deviations of the experimental points from the approximating function (shifted by the assumed systematic error) are regarded as the statistical errors. An optimal description of all the data is achieved by an iterative procedure that minimizes the mean-square deviations with the statistical and systematic errors obtained. The rational functions of the Pade approximation are used to fit the data and construct the resulting covariance matrices.

All experimental data selected by the Brussels and Debrecen groups for the proton and deuteron induced reactions were analyzed by means of the above approach, and some contradictory data at the near-threshold and high-energy regions were estimated. The influence of these data on the recommended uncertainties was studied. Final recommendations for the uncertainty matrices require additional agreements on their group structure. The matrix format required will be developed in collaboration with the above groups towards the end of the summer of 2015.

Experimental data for diagnostic and therapeutic radioisotope production will be analyzed over the second half of 2015. Recommended cross sections together with their uncertainty matrices will be prepared leading up to the final RCM.

3. Discussions

3.1. Decay data

Participants focused their attention on their responsibilities for various nuclear data activities as formulated and agreed at the first research coordination meeting (IAEA report INDC(NDS)-

0630). Decay data evaluations were initially discussed, and agreement was reached on the current status and future work on the various individual work programmes (see Table 4).

Table 4: Status of Decay Data Evaluations, 11 December 2014.

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

Decay scheme	Status	Location*
Monitor reactions		
Cu-61	MAK evaluation completed	DDEP
Zn-62	no volunteer within CRP - adopt ENSDF	ENSDF
Zn-63	ALN evaluation completed	DDEP
Diagnostic γ emitters: Auger electrons and X-rays		
Cu-67	FGK measurements completed. **ACTION**: FGK evaluation on-going for subsequent X/Auger study (no. 2 candidate for Auger code)	(FGK)
Mo-99/Tc-99m	**ACTION**: ALN evaluation on-going in preparation for X/Auger study (no. 3 candidate for Auger code)	(ALN)
In-111	ALN evaluation completed in preparation for X/Auger study (no. 1 candidate for Auger code – "benchmark")	ALN
Positron emitters		
Fe-52	AL evaluation completed	DDEP
Extra: Mn-52m,g	**ACTION**: AL evaluations to be completed by mid-Sept 2015	(DDEP)
Cu-64	MAK re-evaluation completed	DDEP
Ga-66	**ACTION**: FGK measurements underway, and FGK evaluation in 2015/16	(FGK)
As-72	no volunteer within CRP - adopt ENSDF	ENSDF
Se-73	ALN evaluation completed	DDEP
Br-76	**ACTION**: ALN evaluation in 2015	(DDEP)
Y-86	BNL-NNDC measurement planned; FGK evaluation afterwards?	(FGK/ENSDF?)
Zr-89	ALN evaluation completed	DDEP
Tc-94m	ALN evaluation completed	DDEP
I-120	**ACTION**: ALN evaluation in 2015	(DDEP)
Ti-44 (half-life)	FGK evaluation completed	half-life: FGK decay scheme: ENSDF
Therapeutic α emitters: complete U-230 decay chain		
U-230	**ACTION**: AL evaluation in 2015/16	(DDEP)
Th-226	**ACTION**: AL evaluation in 2015/16	(DDEP)
Ra-222	**ACTION**: MAK evaluation in 2015	(DDEP)
Rn-218	**ACTION**: MAK update in 2015	(DDEP)
Po-214	**ACTION**: MAK update in 2015	(DDEP)
Pb-210	**ACTION**: MAK update in 2015	(DDEP)
Bi-210	MAK update completed	DDEP
Po-210	MAK update completed	DDEP
Auger-electron and X-ray emitters		
Ta-178	**ACTION**: FGK evaluation in 2015 in preparation for X/Auger study	(FGK)
Pd-103	ALN evaluation completed in preparation for X/Auger study	ALN
Extra: I-125	**ACTION**: TK evaluation in 2015/16 in preparation for X/Auger study	(TK)
Extra: Cs-131	**ACTION**: ALN evaluation in 2015/16 in preparation for X/Auger study	(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.

Discussions focused on the perceived applications and need for improved decay-data evaluations of specific radionuclides. Volunteers have not come forward within the CRP to evaluate the decay data of ^{62}Zn and ^{72}As – ENSDF was recommended as a suitable source for these data, with the evaluation of ^{62}Zn having occurred in 2012 (see *Nucl. Data Sheets* **113** (2012) 973) and ^{72}As on-going and close to completion/publication as noted at the beginning of 2015.

The decay-data evaluation of ^{52}Fe by Luca in 2013/14 had underlined the importance of undertaking an equivalent exercise for $^{52}Mn^m$ (and ^{52}Mn to a somewhat lesser extent). Populated 100% by EC/β^+ decay of ^{52}Fe with a half-life of 8.27 h, $^{52}Mn^m$ undergoes 96.5% β^+ decay ($E_{\beta+}$ of 2633 keV) with a half-life of 21.1 min. Brief discussions during the course of early 2014 had arrived at the satisfactory agreement that these two additional evaluations would be performed by Luca in 2015.

β^+ emitting analogues can be applied to the quantification of Single Photon Emission Computed Tomography (SPECT) pharmaceuticals. Some β^+ emitters have been used in this manner such as ^{66}Ga (for ^{67}Ga), $^{94}Tc^m$ (for $^{99}Tc^m$) and ^{120}I (for ^{123}I) with SPECT radionuclides, and ^{86}Y (for ^{90}Y) for dosimetry calculations with a therapeutic radionuclide. Kondev reported that ^{66}Ga has been produced on the ATLAS facility at Argonne National Laboratory by means of the $^{66}Zn(p,n)^{66}Ga$ reaction with an enriched ^{66}Zn target, 12-MeV proton beam with an intensity of 5 nA, and irradiation time of 3.5 hours. Initial γ singles and γ–γ coincidence studies have been performed by means of one HPGe detector and Gammasphere to reveal the presence of 40 new γ rays as well as those previously observed. These analytical studies will continue to determine the mixing ratios of the γ transitions and the spins and parities of the resulting nuclear levels of daughter ^{66}Zn. However, a comprehensive decay-data evaluation for such a complex decay scheme may prove problematic on the existing timescale of the on-going CRP.

Single Photon Emission Computed Tomography (SPECT) provides a semi-quantitative and economical means of performing functional imaging, of which $^{99}Tc^m$ in particular and ^{111}In are most commonly employed. These and other specific radionuclides are also judged to be suitable candidates for microdosimetry applications based on the extreme radiotoxicity of their Auger- and conversion-electron emissions, for example: ^{67}Cu, ^{67}Ga, $^{99}Tc^m$, ^{103}Pd, ^{111}In, $^{123,125}I$, ^{131}Cs, ^{178}Ta and ^{201}Tl. Recommended nuclear decay data are in the process of being evaluated for some of these radionuclides in order to benchmark and test the physical model under development at ANU:

Kibedi – ^{125}I;
Kondev – ^{67}Cu and ^{178}Ta;
Nichols – $^{99}Mo/^{99}Tc^m$, $^{103}Pd/^{103}Rh^m$, $^{111}In/^{111}Cd^m$ and ^{131}Cs.

[**Sec. note:** after distant discussions between the authors of these minutes, ^{131}Cs has been added to the list of Auger-electron-emitting radionuclides that require nuclear decay data evaluation and X/Auger-electron studies.]

Both ^{76}Br and ^{120}I are viewed as potentially important radionuclides for future medical studies. Over recent years, ^{76}Br is judged to be an increasingly useful longer-lived radionuclide for incorporation into suitable organic compounds, while ^{120}I has been successfully used in human tomographic studies despite a relatively high positron end-point energy of 4590 keV. However, both of these β^+-emitting radionuclides can be described as challenging from the point of view of evaluations of their decay data. Brief inspections of the recommended data in ENSDF show that ^{76}Br decay constitutes 28EC/19β^+ transitions and 124 γ-ray emissions (plus 38 unplaced γ rays), and ^{120}I decay consists of 40EC/40β^+ transitions and 82 γ-ray emissions (plus 72 unplaced γ rays). Nichols envisaged significant difficulties in his planned evaluations of both decay schemes. Obviously, placement of the significant numbers of unplaced γ rays within the decay schemes would benefit greatly from γ–γ coincidence studies, but this situation would be better clarified after detailed assessments of the existing measured decay data.

^{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 ^{86}Y decay by means of Gammasphere.

Knowledge of the proposed timetable for the NNDC studies would be useful in determining the most appropriate way forward in evaluating and recommending decay data for the CRP.

ACTION: Kondev to enquire with NNDC/ANL staff as to their timetable for the approved ^{86}Y decay-data studies with Gammasphere, along with subsequent availability of data.

The ^{230}U decay chain consists of eight radionuclides, of which six are noteworthy α emitters. Five of the decay schemes have recently been evaluated for inclusion in the IAEA database of actinide decay data (^{218}Rn, ^{214}Po, ^{210}Pb, ^{210}Bi and ^{210}Po), and three require comprehensive evaluations (^{230}U, ^{226}Th and ^{222}Ra). Existing recommended decay data for ^{210}Bi and ^{210}Po have been updated by Kellett, while the apportioning of the remaining effort has been agreed between Kellett and Luca, as listed within Table 4 and scheduled for 2015/16.

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-ray probabilities (intensities) as provided by Capote on request of the cross-section measurer.

ACTION: Kondev to provide Capote with his recommended half-life and main γ-ray emission probabilities for ^{66}Ga by the end of January 2015, and for ^{67}Cu by the end of August 2015.

ACTION: Nichols to provide Capote with all of his recommended/evaluated nuclear decay data for $^{99}Mo/^{99}Tc^m$, $^{103}Pd/^{103}Rh^m$ and $^{111}In/^{111}Cd^m$ by the end of March 2015.

3.2. Cross sections

According to the assignments agreed to at the first research coordination meeting (IAEA report INDC(NDS)-0630), the work scope includes an unusually long list of nuclear reactions to be evaluated. While short exchanges took place during the earlier presentations, more detailed discussions of each reaction were deferred to a later stage in the meeting. During this dedicated period of time, discussions were structured in such a way that the evaluation status of individual nuclear reactions could be determined and fully recorded.

Several important points are highlighted below:

- While cross-section data corrections for outdated gamma-ray intensities can be applied readily, corrections for outdated half-lives are not possible in almost all cases because post end-of-irradiation decay times are almost never reported.
- Experimental data for which the authors do not report uncertainties should be assigned a minimum total uncertainty of 8%, and evaluators of the experimental data should appropriately increase the uncertainties in cases where they are reported and judged to be unrealistically low.

- While availability of uncertainty in the recommended cross sections for all nuclear reactions is desirable, the work scope of the CRP includes the production of uncertainties for the monitor reactions only.
- In order to reduce the amount of data manipulation performed by Ignatyuk, the experimental data evaluators should additionally include in each Excel file they send to Ignatyuk a single table containing all selected data: energies, cross sections, energy uncertainty (where given), cross-section uncertainty (must be TOTAL uncertainty), and indication of author for each data point. Initially, only the total uncertainty is used for fitting and for production of covariances, but in some special cases additional breakdown in cross-section uncertainty will be helpful. The fitting of high-energy proton-induced data also requires significant additional effort. Furthermore, along with the presentation of recommended data, users must appreciate that the region near the threshold should be used with caution.

  ACTION: Ignatyuk to provide an Excel file with an example ready-to-fit data table to the experimental data evaluators.
- In hindsight, from a work coordination standpoint, all available nuclear decay-data files evaluated for the CRP should have been provided to Capote for distribution to the cross-section data evaluators by the end of March 2015. As this was not specified, all other outstanding evaluated and updated nuclear decay-data files need to be available by mid-2016.
- Following a query by the U.S. National Isotope Development Center, a recommended value and uncertainty is required for the absolute emission probability of the 776-keV gamma-ray emitted in the EC/β^+ decay of ^{82}Rb. This gamma-ray is used by the international community to quantify large-scale batch production of ^{82}Sr, and different published values are being applied. After some discussion, LANL was directed to use the absolute emission probability reported in the 2003 decay data evaluation of Tuli of 15.08(16)% (*Nucl. Data Sheets* **98** (2003) 209).
- No cross-section measurements for neutron-induced reactions will be undertaken by CRP participants, because the agreed focus is defined to be charged-particle induced reactions. Furthermore, good quality cross-section data can be extracted from available evaluations of neutron induced reactions (e.g. data contained within IAEA reports INDC(NDS)-0526, 0546 and 0584, as produced for the IRDFF library and available on-line from the IAEA-NDS webpage). Nagai will also provide measured yield values from irradiated oxide samples to be used as benchmarks of the available evaluated data.
- CRP evaluations of charged-particle induced reactions can and will be used to validate new theoretical models that describe the reaction cross sections for complex-incident particles, with emphasis on weakly-bound incident particles (e.g. deuterons). Other plans include the further development of the microscopic description of elastic and inelastic deuteron breakup, including the effects of pre-equilibrium emission in the decay that follows inelastic deuteron breakup, as well as studies of the direct (n,d) and (p,d) pickup mechanisms.
- Participants discussed different options for the publication of the final technical report of the CRP, and considered the advantages and disadvantages of a peer-review publication comparted with an IAEA-STI technical report. Capote suggested exploring the possibility of publishing a substantial paper in *Nuclear Data Sheets* (100-150 pages), combined with full data dissemination on the IAEA-NDS website. [**Sec. note:** editor of *Nuclear Data Sheets* has confirmed interest in publishing such a paper - he may attend the next RCM to assess the proposed publication, and explain the preparative process in detail.]

4. Recommendations

Various types of radionuclides were considered on the basis of their modes of production, decay characteristics, and existing and potential applications in nuclear medicine:

- monitor reactions,
- diagnostic γ-ray emitters,
- positron emitters,
- therapeutic α emitters,
- therapeutic electron and X-ray emitters.

All progress was defined in terms of individual data sets, measurements and subsequent evaluations, as shown in the relevant columns of Tables 4 to 10. Some of the resulting actions are required fairly promptly, while others are longer term, constituting the important components of the final database for delivery and assembly in 2016 at the envisaged conclusion of the on-going coordinated research project.

At the commencement of the programme, proposed procedures for the initiation of the various work packages were agreed in two different forms:

<u>Decay data</u>

- Compile and evaluate decay data (see Table 4), and deliver recommended data sets before the third research coordination meeting (May/June 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);
    - reviewprocesses to be implemented promptly, and all reviewers' comments and criticism taken into consideration by the responsible evaluator prior to final database release in ENSDF format.
- Auger-electron data for specific radionuclides require improved quantification with good accuracy, detail and confidence prior to incorporation in the recommended decay-data files (see Table 4)
    - on-going studies to develop a suitable modeling code will continue (Kibedi, Kondev and others);
    - compile and evaluate Auger-electron data with respect to the modeling process, and provide recommended Auger-electron decay data in late 2015 (before the third research coordination meeting) for their insertion in the relevant files of the final database.

<u>Cross sections</u>

- Compile reaction data, and assess and deliver files before third research coordination meeting, June/July 2016 (see Tables 5 to 10). Assessed data should be provided in a 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;

- provide full bibliographic lists in the style of IAEA Technical Reports Series no. 473;
- 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.

Some of the actions involve mixed combinations of measurements and assessments-evaluations. Under these circumstances, logic decrees that the measurements will be undertaken and reported prior to the final stage of full data assessment/evaluation.

During the course of the various discussions outlined above, tables of activities and actions were prepared and agreed upon (Tables 4 to 10). Table 4 summarizes the status of the recommended decay-data files for all chosen medical radionuclides, along with agreed actions to be performed in 2015/16, whereas Tables 5 to 10 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.

Table 5: Cross-section studies of monitor reactions.

Data for fitting should be provided in a list form (EXCEL file) with indication of overall uncertainty for each data point. Already provided data should be checked for compliance with this requirement.

Cross sections	Agreed responsibilities, status and actions
fitting of cross-section data	IPPE: agreed that monitor reaction data will be sent to Ignatyuk by March 2015; fitting can therefore be completed by summer, leaving substantial contingency for iteration prior to next RCM.
$^{27}Al(p,x)^{22,24}Na$	LANL (re-assess up to 800 MeV): data collected; de-selection in progress; projected completion by March 2015.
$^{27}Al(d,x)^{22,24}Na$	Debrecen / VUB (re-assess): completed; data sent to Ignatyuk; data fitted.
$^{27}Al(^{3}He,x)^{22,24}Na$	Debrecen / VUB (re-assess): completed; data sent to Ignatyuk.
$^{27}Al(\alpha,x)^{22,24}Na$	Kim (measure); Debrecen / VUB (assess): measurement of Kim will be below threshold.; completed; data sent by Tárkányi to Ignatyuk
$^{nat}Ti(d,x)^{46}Sc$	Debrecen / VUB (re-assess): Spahn and Lebeda to send additional data to Hermanne by end of December 2014.
$^{nat}Ti(^{3}He,x)^{48}V$	Lebeda (measure and re-assess up to 46 MeV): send data to Ignatyuk by February 2015.
$^{nat}Ni(d,x)^{56,58}Co$	Debrecen / VUB (measure and re-assess): completed; data sent to Ignatyuk.
$^{nat}Cu(p,x)^{58}Co$	Kim (measure), LANL (measure and assess up to 100 MeV): measurement of Kim completed; will be added to LANL evaluation with additional data from Lebeda (by December 2014); send to Ignatyuk by March 2015.
$^{nat}Cu(p,x)^{62,63,65}Zn$	Kim (measure); Debrecen / VUB (measure and re-assess): measurement completed; will be added to VUB evaluation; send data to Ignatyuk by March 2015.
$^{nat}Cu(d,x)^{62,63,65}Zn$	Debrecen / VUB (measure and re-assess): completed; data sent to Ignatyuk.
$^{nat}Cu(\alpha,x)^{66,67}Ga$, ^{65}Zn	Kim (measure and re-assess): Measurement completed; Hermanne will assess and send data to Ignatyuk by March 2015; completed assessment of $^{63}Cu(\alpha,x)^{66}Ga$ to be transferred by Hussain to Hermanne.
$^{nat}Mo(p,x)^{96}Tc^{g+m}$	Debrecen / VUB / Lebeda (assess): newly measured data from Lebeda to be added by June 2015; Tárkányi to send data to Ignatyuk by October 2015.
previously evaluated cross sections	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 covariances. All reactions for protons except $^{nat}Cu(p,x)^{56}Co$ completed and sent to Ignatyuk; LANL will assess up to 200 MeV by March 2015; additional monitor reactions were added; $^{nat}Ti(p,x)^{46}Sc$ data were sent to Ignatyuk and fitted. All reactions listed previously for deuterons are completed and sent to Ignatyuk. All ^{3}He reactions listed previously are completed and sent to Ignatyuk. $^{nat}Cu(^{3}He,x)^{66}Ga$, ^{63}Zn, ^{65}Zn and $^{nat}Ti(^{3}He,x)^{51}Cr$ data will be sent by Tárkányi to Ignatyuk by May 2015. All ^{4}He reactions listed previously are completed and have been sent to Ignatyuk.

Table 6: Cross-section studies for the production of diagnostic γ emitters.
Data for fitting should be provided in a list form (EXCEL file) with indication of overall uncertainty for each data point. Already provided data should be checked for compliance with this requirement.

Cross sections	Agreed responsibilities, status and actions
fitting of cross-section data	IPPE: all fitting to be completed by the next RCM.
$^{90}Zr(n,p)^{90}Y^{g+m}$	Nagai (measure), ITA (assess) - see also IRDFF (http://www-nds.iaea.org/IRDFF) and IAEA Technical Reports Series No. 473: no cross-section measurements planned for CRP; Nagai to provide measured yield values on oxide samples; Carlson to extend excitation functions up to 40 MeV and assess; Carlson to send data to Capote by July 2015.
$^{100}Mo(n,2n)^{99}Mo$	ITA / Nagai (assess): no cross-section measurements planned for CRP; Nagai to provide measured yield values on oxide samples; Carlson to extend excitation functions up to 40 MeV, assess and send to Capote by July 2015.
$^{100}Mo(p,2n)^{99}Tc^{g+m}$	NPI (measure), ITA / Debrecen / VUB (assess): Lebeda to complete measurement and send to Carlson by June 2015; Carlson to assess and send a consistent data set to Ignatyuk by October 2015.
$^{100}Mo(p,pn)^{99}Mo$	NPI (measure), ITA / Debrecen / VUB (assess): Lebeda to complete measurement and send to Carlson by June 2015; Carlson to assess and send a consistent data set to Ignatyuk by October 2015.
$^{100}Mo(d,3n)^{99}Tc^{g+m}$	NPI / ITA / Debrecen / VUB (assess): Lebeda and Carlson to assess and send to Ignatyuk by October 2015.
$^{100}Mo(d,p2n)^{99}Mo$	NPI / ITA / Debrecen / VUB (assess): Lebeda and Carlson to assess and send to Ignatyuk by October 2015.
$^{100}Mo(\gamma,n)^{99}Mo$	Naik / Kim (measure and assess): Measurements are completed. Naik to assess and submit data to Capote by October 2015.
$^{238}U(\gamma,f)^{99}Mo$	Naik (measure and assess) - measurements are completed up to 17 MeV; Naik to assess and submit data to Capote by October 2015.
$^{68}Zn(\gamma,p)^{67}Cu$	Naik / Kim (measure and assess): measurements are completed; data to be submitted to Capote by October 2015.
$^{67}Zn(n,p)^{67}Cu$	Nagai (measure), ITA (assess) - see also IRDFF (http://www-nds.iaea.org/IRDFF) and IAEA Technical Reports Series No. 473: assessment is not necessary; no cross-section measurements planned for CRP; Nagai to provide measured yield values on oxide samples.
$^{68}Zn(n,x)^{67}Cu$	Nagai (measure), ITA (assess): assessment is not necessary; no cross-section measurements planned for CRP; Nagai to provide measured yield values on oxide samples.
$^{64}Zn(n,p)^{64}Cu$	Nagai (measure), ITA (assess) - see also IRDFF (http://www-nds.iaea.org/IRDFF), IAEA Technical Reports Series No. 473, and INDC(NDS)-0526: assessment is not necessary; no cross-section measurements planned for CRP; Nagai to provide measured yield values on oxide samples.
$^{112}Cd(p,2n)^{111}In$	Debrecen / VUB (assess): completed; sent to Ignatyuk.
$^{124}Xe(p,x)^{121}I$	Debrecen / VUB (assess): completed; sent to Ignatyuk.
$^{124}Xe(p,2n)^{123}Cs$	Debrecen / VUB (assess): completed; sent to Ignatyuk.
$^{124}Xe(p,pn)^{123}Xe$	Debrecen / VUB (assess): completed; sent to Ignatyuk.

Table 6: Cross-section studies for the production of diagnostic γ emitters (continued).
Data for fitting should be provided in a list form (EXCEL file) with indication of overall uncertainty for each data point. Already provided data should be checked for compliance with this requirement.

Cross sections	Agreed responsibilities, status and actions
reactions leading to ^{51}Cr	Debrecen (re-assess some noted production routes of ^{51}Cr): in progress; to be sent to Ignatyuk by March 2015; reactions being assessed include $^{51}V(p,n)^{51}Cr$, $^{nat}V(p,x)^{51}Cr$, $^{nat}V(d,x)^{51}Cr$, $^{nat}Ti(\alpha,x)^{51}Cr$ and $^{nat}Ti(^{3}He,x)^{51}Cr$.
$^{nat}Fe(p,x)^{51}Cr$	Kim (measure and assess): measurement completed and sent to Tárkányi; assessment to be sent to Ignatyuk by March 2015.
$^{203}Tl(p,2n)^{202}Pb^{m}$	Debrecen / VUB (re-assess): completed; sent to Ignatyuk
$^{203}Tl(p,3n)^{201}Pb$	Debrecen / VUB (re-assess): completed; sent to Ignatyuk
$^{203}Tl(p,4n)^{200}Pb$	Debrecen / VUB (re-assess): completed; sent to Ignatyuk
$^{nat}W(\alpha,x)^{186,188}Re$	Kim (measure and assess): measurement in progress; assessment to be completed by June 2015; suggested that no cross section should be recommended because values are too low to be useful for production.

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

Data for fitting should be provided in a list form (EXCEL file) with indication of overall uncertainty for each data point. Already provided data should be checked for compliance with this requirement.

Cross sections	Agreed responsibilities, status and actions
fitting of cross-section data	IPPE: all fitting to be completed by the next RCM.
Production of ^{52}Fe	Reactions for production of ^{52}Fe production moved to the generator section.
$^{58}Ni(p,\alpha)^{55}Co$	Lahore (assess): completed; sent to Ignatyuk; to be re-sent by Lahore in required format.
$^{54}Fe(d,n)^{55}Co$	Lahore (assess): completed; sent to Ignatyuk; to be re-sent in required format.
$^{56}Fe(p,2n)^{55}Co$	Lahore (assess): completed; sent to Ignatyuk; to be re-sent by Lahore in required format, taking into account new measurements by Kim.
$^{nat}Fe(p,x)^{55}Co$	Kim (measure), Lahore (assess): measurements are completed; assessment in progress; send to Ignatyuk by August 2015.
$^{61}Ni(p,n)^{61}Cu$	Jülich (measure and assess): in progress; to be completed by December 2015; determined that measurements on ^{nat}Ni targets are inadequate to describe $^{61}Ni(p,n)^{61}Cu$ reaction.
$^{nat}Ni(d,x)^{61}Cu$	Reaction is evaluated as a monitor, but can also be cost-effectively used for production of positron-emitting ^{61}Cu.
$^{64}Zn(p,\alpha)^{61}Cu$	Lebeda (measure and assess): in progress; to be completed by December 2015.
$^{66}Zn(p,n)^{66}Ga$	Lahore (assess): completed; sent to Ignatyuk; to be re-sent in required format.
$^{63}Cu(\alpha,n)^{66}Ga$	Lahore (assess): completed; sent to Ignatyuk; transferred to Hermanne for inclusion as part of $^{nat}Cu(\alpha,x)^{66}Ga$ monitor reaction assessment.
$^{68}Zn(p,n)^{68}Ga$	Jülich (measure and assess): assessment in progress; to be completed by March 2015; necessity of new measurements to be determined by Spahn.
$^{65}Cu(\alpha,n)^{68}Ga$	Jülich (assess): measurements completed; evaluation in progress; data to be sent to Ignatyuk by March 2015; Kim will send data for $^{nat}Cu(\alpha,x)^{68}Ga$ to Spahn by end of December 2014.
$^{93}Nb(p,x)^{90}Nb$	Kim (measure and assess): measurements completed; assessment by Hussain; send data to Ignatyuk by August 2015.
$^{89}Y(\alpha,x)^{90}Nb$	Kim (measure and assess): measurements completed; assessment by Hussain; send data to Ignatyuk by August 2015.
$^{nat}Y(\alpha,x)^{89}Zr$	Kim (measure and assess): measurements completed; this excitation function will not be recommended due to high beam energies and low yields.
$^{nat}Ge(p,xn)^{72}As$	Jülich (measure), Lahore (assess): additional measurements by VUB / Debrecen completed; will be provided to Lahore by June 2015; assessment in progress; Hussain to determine if Jülich measurements are necessary.
$^{75}As(p,3n)^{73}Se$	Lebeda (measure), Lahore (assess): measurement in progress; data sent to Lahore by March 2015; assessment to be completed and sent to Ignatyuk by June 2015.
$^{72}Ge(\alpha,3n)^{73}Se$	Lahore (assess): assessment in progress; to be completed and sent to Ignatyuk by August 2015.
$^{76}Se(p,n)^{76}Br$	Jülich (measure), Lahore (assess): completion of measurement intended by November 2015; assessment to be completed in parallel with measurement by November 2015.
$^{77}Se(p,2n)^{76}Br$	Jülich (measure), Lahore (assess): completion of measurement intended by November 2015; assessment to be completed in parallel with measurement by November 2015
$^{75}As(\alpha,3n)^{76}Br$	Lahore (assess): completed; sent to Ignatyuk; will be re-sent by Lahore in required format.

Table 7: Cross-section studies for the production of positron emitters (continued).
Data for fitting should be provided in a list form (EXCEL file) with indication of overall uncertainty for each data point. Already provided data should be checked for compliance with this requirement.

Cross sections	Agreed responsibilities, status and actions
$^{86}Sr(p,n)^{86}Y$	Lahore (assess): completed; sent to Ignatyuk; to be re-sent by Lahore in required format.
$^{88}Sr(p,3n)^{86}Y$	Lahore (assess): completed; sent to Ignatyuk; to be re-sent by Lahore in required format.
$^{85}Rb(\alpha,3n)^{86}Y$	Lahore (assess): completed; sent to Ignatyuk; to be re-sent by Lahore in required format.
$^{89}Y(p,n)^{89}Zr$	ITA (assess): in progress; send data to Ignatyuk by June 2015.
$^{89}Y(d,2n)^{89}Zr$	Lebeda (measure and assess): measurement complete; assessment in progress; send data to Ignatyuk by March 2015.
$^{94}Mo(p,n)^{94m}Tc$	ITA (assess): in progress; send data to Ignatyuk by June 2015.
$^{92}Mo(\alpha,x)^{94m}Tc$	ITA (assess): in progress; send data to Ignatyuk by June 2015.
$^{110}Cd(p,n)^{110m}In$	Debrecen / VUB (assess): assessment in progress; send data to Ignatyuk by March 2015; additional reactions to be considered include $^{107}Ag(\alpha,n)^{110m}In$, $^{109}Ag(^{3}He,2n)^{110m}In$ and $^{110}Cd(d,2n)^{110m}In$.
$^{120}Te(p,n)^{120}I$	Lahore (assess): in progress, send data to Ignatyuk by March 2015.
$^{122}Te(p,3n)^{120}I$	Lahore (assess): in progress, send data to Ignatyuk by March 2015.

Table 8: Cross-section studies for the production of positron emitters: generators.
Data for fitting should be provided in a list form (EXCEL file) with indication of overall uncertainty for each data point. Already provided data should be checked for compliance with this requirement.

Generator	Cross sections	Agreed responsibilities, status and actions
$^{62}Zn/^{62}Cu$		PET analogue of therapeutic ^{67}Cu.
	$^{63}Cu(p,2n)^{62}Zn$	Debrecen / VUB (measure and assess): assessment of $^{63}Cu(p,2n)^{62}Zn$, $^{60}Ni(\alpha,2n)^{62}Zn$, $^{60}Ni(^{3}He,n)^{62}Zn$, $^{63}Cu(d,3n)^{62}Zn$ in progress; send data to Ignatyuk by March 2015.
$^{68}Ge/^{68}Ga$		PET analogue of proposed/new therapeutic ^{67}Ga.
	$^{nat}Ga(p,xn)^{68}Ge$	Debrecen / VUB (measure and assess): completed; data sent to Ignatyuk; fitted; data for $^{nat}Ga(p,x)^{69}Ge$ also sent to Ignatyuk, but will not be fitted.
	$^{69}Ga(p,2n)^{68}Ge$	Debrecen / VUB (measure and assess): completed; data sent to Ignatyuk and fitted.
	$^{71}Ga(p,4n)^{68}Ge$	Debrecen / VUB (measure and assess): only one data set exists; no recommendation will be made.
$^{72}Se/^{72}As$	$^{75}As(p,4n)^{72}Se$	LANL (assess): assessment in progress; send data to Ignatyuk by March 2015.
	$^{nat}Br(p,x)^{72}Se$	LANL (assess): assessment in progress; send data to Ignatyuk by March 2015.
$^{82}Sr/^{82}Rb$	$^{nat}Rb(p,xn)^{82}Sr$ $^{85}Rb(p,4n)^{82}Sr$	LANL (assess): assessment in progress; send data to Ignatyuk by March 2015; LANL 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).
$^{52}Fe/^{52}Mn^{m}$	$^{55}Mn(p,4n)^{52}Fe$	Lahore (assess): assessment in progress; to be completed by August 2015.
	$^{nat}Ni(p,x)^{52}Fe$	Lahore (assess): assessment in progress; to be completed by August 2015.
	$^{52}Cr(^{3}He,3n)^{52}Fe$	Lahore (assess): assessment in progress; to be completed by August 2015; $^{50}Cr(\alpha,2n)^{52}Fe$ reaction will also be included in Hermanne measurements.
$^{110}Sn/^{110}In^{m}$	Main reactions leading to the parent nucleus	PET analogue of therapeutic ^{111}In and $^{114}In^{m}$. Debrecen / VUB (assess): assessment of $^{nat}Cd(^{3}He,x)^{110}Sn$, $^{nat}Cd(\alpha,x)^{110}Sn$, and $^{nat}In(p,x)^{110}Sn$ in progress; send data to Ignatyuk by March 2015.
$^{128}Ba/^{128}Cs$	Main reactions leading to the parent nucleus	PET analogue of proposed/new therapeutic ^{131}Cs. Debrecen / VUB (assess): $^{133}Cs(p,5n)^{128}Ba$ is the only relevant reaction; assessment in progress; send data to Ignatyuk by March 2015.
$^{122}Xe/^{122}I$	Main reactions leading to the parent nucleus	PET analogue of therapeutic ^{123}I, ^{125}I and ^{131}I. Debrecen / VUB (assess): assessment of $^{127}I(p,6n)^{122}Xe$, $^{127}I(d,7n)^{122}Xe$ and $^{124}Xe(p,x)^{122}Xe$ in progress; send data to Ignatyuk by March 2015.
$^{118}Te/^{118}Sb$	Main reactions leading to the parent nucleus	PET analogue of proposed/new therapeutic ^{117}Sb and ^{119}Sb. Debrecen / VUB (assess): assessment of $^{122}Te(p,x)^{118}Sb$, $^{nat}Sb(p,x)^{118}Sb$, $^{nat}Sn(\alpha,x)^{118}Sb$ in progress; send data to Ignatyuk by March 2015.
$^{140}Nd/^{140}Pr$	Main reactions leading to the parent nucleus	LANL (assess): assessment of $^{nat}Ce(^{3}He,xn)^{140}Nd$ and $^{141}Pr(p,2n)^{140}Pr$ in progress; data sent to Ignatyuk by March 2015; if available, $^{141}Pr(d,3n)^{140}Nd$ and $^{nat}Ce(\alpha,x)^{140}Nd$ data to be provided by Tárkányi.
$^{44}Ti/^{44}Sc$	Main reactions leading to the parent nucleus	Jülich (assess cross sections): assessment recommends new cross-section measurements; measurements for proton-induced reactions on ^{nat}Sc have been completed and will be sent to Ignatyuk by March 2015; deuteron-induced reaction measurements are also recommended, and are planned for completion by December 2015. [^{44}Ti half-life evaluation completed by Kondev: $t_{1/2}$ = 59.1 ± 0.3 y recommended]

Table 9: Cross-section studies for the production of therapeutic α emitters.

Cross sections	Agreed responsibilities, status and actions
fitting of cross-section data	IPPE: all fitting to be completed by the next RCM.
^{229}Th(α)^{225}Ra(β^{-})^{225}Ac(α) decay chain to ^{213}Bi:	
^{232}Th(p,x)^{225}Ra	LANL (assess): in progress; send data to Ignatyuk by March 2015.
^{232}Th(p,x)^{225}Ac	LANL (assess): in progress; send data to Ignatyuk by March 2015.
^{226}Ra(p,2n)^{225}Ac	LANL (assess): new evaluation is not necessary.
^{232}Th(p,x)^{227}Ac	LANL (assess): in progress; send data to Ignatyuk by March 2015; Gauvin data to be energy-shifted based on calculated reaction threshold energy.
^{230}U(α)^{226}Th(α) decay chain:	
^{231}Pa(d,3n)^{230}U	Lebeda (assess): limited data available; assessment in progress; send data to Ignatyuk by end of December 2014.
^{231}Pa(p,2n)^{230}U	Lebeda (assess): limited data available; assessment in progress; send data to Ignatyuk by end of December 2014.
^{232}Th(p,3n)^{230}Pa(β^{-})^{230}U	Lebeda (assess): limited data available; assessment in progress; send data to Ignatyuk by end of December 2014.
^{227}Th(α)^{223}Ra(α) decay chain	
^{232}Th(p,x)^{227}Th	LANL (assess): in progress; send data to Ignatyuk by March 2015.

Table 10: Cross-section studies for the production of therapeutic electron and X-ray emitters.

Cross sections	Agreed responsibilities, status and actions
fitting of cross-section data	IPPE: all fitting to be completed by the next RCM.
^{30}Ba(n,γ)^{131}Ba(EC)^{131}Cs	Nagai (assess): assessment in progress: send data to Capote by April 2015.
^{131}Xe(p,n)^{131}Cs	Debrecen / VUB (measure and assess): completed and sent to Ignatyuk.
^{133}Cs(p,3n)^{131}Ba(EC)^{131}Cs	Debrecen / VUB (measure and assess): completed and sent to Ignatyuk; require decay-data evaluation and Auger-electron study of ^{131}Cs EC decay.
^{176}Hf(α,2n)^{178}W(EC)^{178}Ta	Kim (measure and assess): measurement made by Debrecen; Tárkányi to send assessment to Ignatyuk by May 2015; ^{181}Ta(p,4n)^{178}W is also completed; send data to Ignatyuk by May 2015.
^{nat}Hf(p,x)^{178}Ta	Kim (measure and assess): measurement completed; recommendation is unnecessary because direct production is unpractical due to short $t_{1/2}$ of the daughter.
^{103}Rh(p,n)^{103}Pd ^{103}Rh(d,2n)^{103}Pd	Tárkányi to consider latest decay-data evaluation (to be provided by ALN).

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 in 2013/14 as formulated at the first research coordination meeting in December 2012 (IAEA report INDC(NDS)-0630). Both cross-section and decay-data measurements and evaluations were discussed in detail. Specific deadlines were set leading up to the third research coordination meeting scheduled for May/June 2016. A primary aim at the conclusion of this coordinated research project will be 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 a series of such 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 4 to 10 in terms of assigned responsibilities for nuclear data measurements and assessments/evaluations.

ACTIONS, 8-12 December 2014

No.	Agreed action	
1	**Decay data:** ^{66}Ga: half-life and main γ-ray emission probabilities by the end of January 2015. Decay-data measurements and full evaluation in 2015/16.	Kondev
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, Kibedi
3	$^{99}Mo/^{99}Tc^{m}$: nuclear decay-data evaluation on-going, with completion by the end of March 2015. Subsequent X/Auger study later in 2015.	Nichols, Kibedi
4	Provide Capote and Tárkányi with nuclear decay-data evaluation for ^{103}Pd by the end of March 2015.	Nichols
5	$^{103}Pd/^{103}Rh^{m}$: X/Auger study in 2015/16.	Kibedi
6	^{125}I: nuclear decay-data evaluation and subsequent X/Auger study in 2015.	Kibedi
7	^{131}Cs: nuclear decay-data evaluation in 2015, and subsequent X/Auger study in 2016.	Nichols, Kibedi
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, Kibedi
9	^{52}Mn and $^{52}Mn^{m}$: nuclear decay-data evaluations to be completed by mid-Sept 2015.	Luca
10	^{76}Br, ^{120}I: decay-data evaluations in 2015.	Nichols
11	^{86}Y: determine timetable for BNL decay measurements, and subsequent availability of data – nuclear decay-data evaluation?	Kondev
12	^{178}Ta: nuclear decay-data evaluation for subsequent X/Auger study in 2016.	Kondev, Nichols
13	^{230}U decay chain: shared updates and full nuclear decay-data evaluations in 2015/16 as agreed (see also Table 4).	Kellett, Luca
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
15	For other cross-sections actions see Tables 5-10.	

APPENDIX 1

Agenda

Second Research Coordination Meeting on
"Nuclear data for charged-particle monitor reactions and medical isotope production"

IAEA Headquarters, Vienna, Austria
8 – 12 December 2014

Meeting Room MOE03

Monday, 8 December

08:30 – 09:30 **Registration** (IAEA Registration desk, Gate 1)
09:30 – 10:00 **Opening Session**
Welcoming address and Introductory Remarks – Roberto Capote Noy
Election of Chairman and Rapporteur
Adoption of Agenda
10:00 – 10:45 **Administrative and Financial Matters related to participants**
(and coffee break, if needed)

Decay Data (DD): F. Kondev, A.L. Nichols, A. Luca, M. Kellett, T. Kibedi
Reaction measurements (RM): A. Hermanne, F. Tarkanyi, O. Lebeda, K. Guinyun, I. Spahn, Y. Nagai,
F.M. Nortier, H. Naik
Reaction theory and evaluations (EV): B.V. Carlson, M. Hussain, A.V. Ignatyuk

10:45 – 12:30 **Session 1:** Review of work done (DD, ~30-*40 min each*)
12:30 – 14:00 **Lunch**
14:00 – 18:00 **Session 2:** Review of work done (RM, *~30-40 min each*)
(*Coffee break as needed)*

Tuesday, 9 December

09:00 – 12:30 **Session 3:** Review of work done (DD/RM ~3*0-40 min each*)
(*Coffee break as needed)*
12:30 – 14:00 **Lunch**
14:00 – 18:00 **Session 4:** Review of work done (RM/EV ~3*0-40 min each*)
(*Coffee break as needed)*

Wednesday, 10 December

09:00 – 12:30 **Session 5:** Discussion of on-going and future work, deliverables, data needs (DD)
(*Coffee break as needed)*
12:30 – 14:00 **Lunch**
14:00 – 18:00 **Session 6:** Discussion of on-going and future work, deliverables (RM)
(*Coffee break as needed)*

19:00 ***Dinner at a restaurant in the city***
(see separate information in folder)

Thursday, 11 December

09:00 – 12:30 **Session 7:** Discussion of on-going and future work, deliverables (EV)

(*Coffee break as needed)*

12:30 – 14:00 **Lunch**

14:00 – 18:00 **Drafting of the Meeting Summary Report**

(*Coffee break as needed)*

Friday, 12 December

09:00 – 12:30 **Review of the Meeting Summary Report**

(*Coffee break as needed)*

12:30 – 14:00 **Lunch**

14:00 – 16:00 **Review of the Meeting Summary Report** (continued)

16:00 **Closing of the Meeting**

APPENDIX 2

LIST OF PARTICIPANTS

2nd Research Coordination Meeting on
Nuclear data for charged-particle monitor reactions and medical isotope production
8-12 December 2014
Vienna, Austria

BELGIUM
Alex HERMANNE
Cyclotron Laboratory
Vrije Universiteit Brussel
Laarbeeklaan 103
1090 Brussels
Tel: +32 2 477 48 51
E-mail: aherman@vub.ac.be

BRAZIL
Brett Vern CARLSON
Instituto Tecnologico de Aeronautica (ITA)
Praça Mal. Eduardo Gomes, 50
Vila das Acácias
12228-900 Sao Jose dos Campos, SP
Tel: +55 12 3947 6881
E-mail: brett@ita.br

CZECH REPUBLIC
Ondrej LEBEDA
Nuclear Physics Institute (NPI)
Academy of Sciences of the Czech Rep.
Husinec-Rez, cp. 130
25068 Rez
Tel: +420 266 172 136
E-mail: lebeda@ujf.cas.cz

FRANCE
Mark KELLETT
Laboratoire National Henri Becquerel
CEA-Centre d'Etudes de Saclay
91191 Gif-sur-Yvette Cedex
Tel. +33 1 69 08 27 76
E-mail: mark.kellett@cea.fr

GERMANY
Ingo SPAHN
Forschungszentrum Jülich (FZJ)
PO Box 1913
52425 Jülich
Tel: +49 2461 61 4450
E-mail: i.spahn@fz-juelich.de

HUNGARY
Ferenc T. TARKANYI
Institute of Nuclear Research
Hungarian Academy of Sciences
Bem ter 18/c, PO Box 51
4001 Debrecen
Tel: +36 52 509 200
E-mail: tarkanyi@atomki.mta.hu

INDIA
Haladhara NAIK
Bhabha Atomic Research Centre (BARC)
Trombay
Mumbai, Maharashtra 400 085
Tel: +91 22 2559 4569
E-mail: naikh@barc.gov.in

JAPAN
Yasuki NAGAI
Japan Atomic Energy Agency (JAEA)
2-4 Shirane, Shirakata, Tokaimura
Naka, Ibaraki-ken 319-1195
Tel: +81 29 282 5470
E-mail: nagai@rcnp.osaka-u.ac.jp

KOREA, Republic of
Guinyun KIM
Kyungpook National University
1370 Sankyuk-dong, Puk-gu
Daegu 702-701
Tel: +82 53950 5320
E-mail: gnkim@knu.ac.kr

PAKISTAN
Mazhar HUSSAIN
Government College University
Katchery Road
54000 Lahore
Tel: +92 3214334370
E-mail: dr.mazharhussain@gcu.edu.pk

ROMANIA
Aurelian LUCA
National Institute of Physics and Nuclear Engineering "Horia Hulubei"
Str. Reactorului Nr 30
PO Box MG-6
077125 Magurele
Tel: +40 21 404 61 63
E-mail: aluca@nipne.ro

RUSSIAN FEDERATION
Anatoly IGNATYUK
Inst. for Physics & Power Engineering (IPPE)
Ploshad Bondarenko 1
249033 Obninsk, Kaluzhskaya Oblast
Tel: +7 48439 98035
E-mail: ignatyuk@ippe.ru

UNITED KINGDOM
Alan L. NICHOLS
38 Mattock Way
Abingdon
OX14 2PQ
Tel. +44 1235524077
E-mail: alanl.nichols@btinternet.com

UNITED STATES OF AMERICA
Jonathan W. ENGLE
Los Alamos National Laboratory
PO Box 1663
Los Alamos, New Mexico 87545
Tel.: +1 505 665 3791
E-mail: jwengle@lanl.gov

UNITED STATES OF AMERICA
Filip KONDEV
Argonne National Laboratory (ANL)
9700 South Cass Avenue
Argonne, IL 60439
Tel. +1 630 252 4484
E-mail: kondev@anl.gov

UNITED STATES OF AMERICA
Francois Meiring NORTIER
Los Alamos National Laboratory
PO Box 1663
Los Alamos, NM 87545
Tel: +1 505 667 9501
E-mail: meiring@lanl.gov

IAEA
Roberto Capote Noy
Scientific Secretary
Nuclear Data Section
Division of Physical and Chemical Sciences
Tel.: +43 1 2600 21713
E-mail: r.capotenoy@iaea.org

IAEA
Paraskevi Dimitriou
Nuclear Physicist (Codes Development)
Nuclear Data Section
Division of Physical and Chemical Sciences
Tel.: +43 1 2600 21708
E-mail: p.dimitriou@iaea.org

IAEA
Marco Verpelli
Nuclear Physicist
Nuclear Data Section
Division of Physical and Chemical Sciences
E-mail: m.verpelli@iaea.org

APPENDIX 3

Meeting Photo

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