Argonne NATIONAL LABORATORY

Member of the US Nuclear Data Program

Report on Technical Meeting on "Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data"

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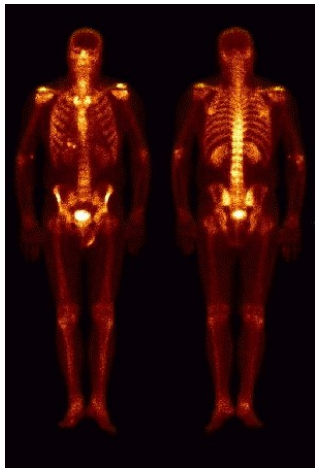
U.S. DEPARTMENT OF ENERGY

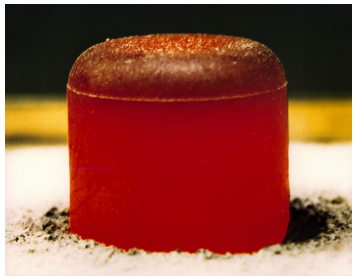
Isotopes (What, where and why?)

- **Stable and radioactive** isotopes play critical roles in a variety of technological applications important to modern society:
  - ✓ Basic scientific research
  - ✓ Nuclear Medicine:
    - Diagnostic
    - Therapeutic
    - Imaging
    - Radiation Source
  - ✓ Oil Industry
  - ✓ National Security and HMS
  - ✓ Power sources (e.g. nuclear batteries)
  - ✓ Tracers
  - ✓ Many (other) commercial applications

^{99m}Tc



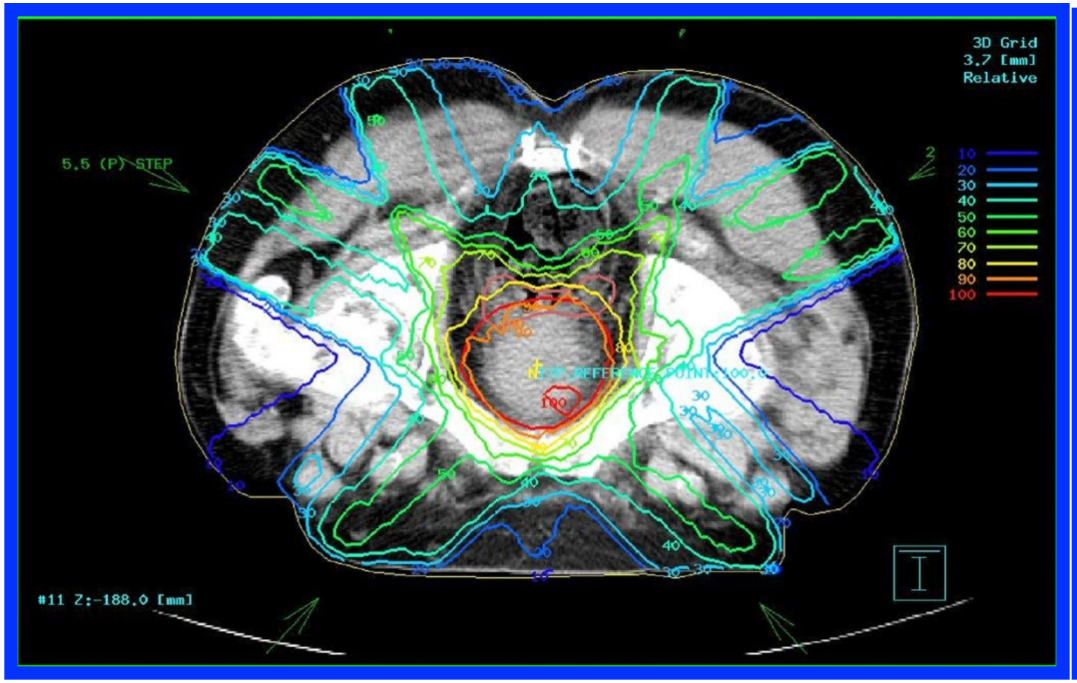
$^{238}PuO_2$

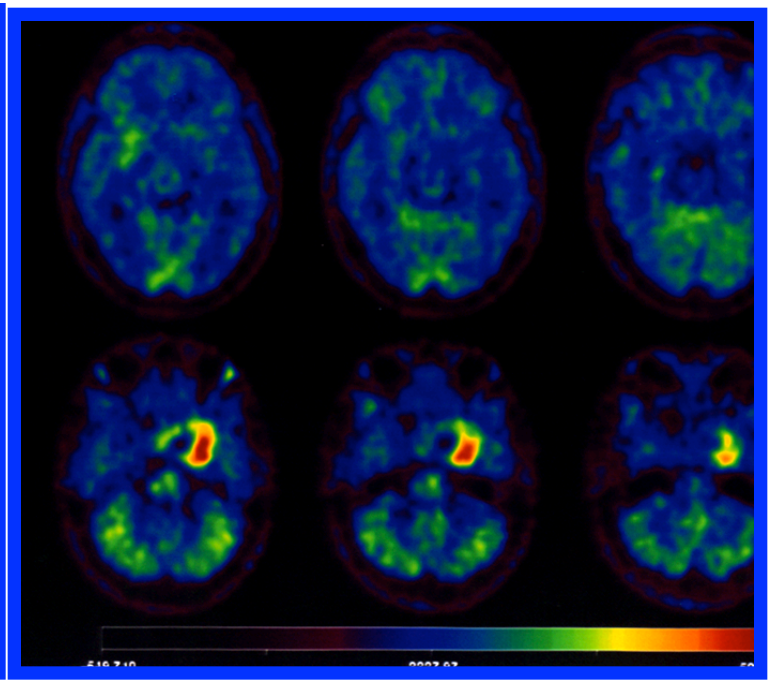


- Production is either using a **nuclear reactor** or an **accelerator**

Nuclear Data for Medical Applications

Rationale: Cancer therapy & Diagnosis





Beneficiaries: medical physicists, radioisotope producers, scientists …

Objectives: Improve data for medical radioisotope production, and for patient dose delivery calculations in radiotherapy

Nuclear Medicine: ND Considerations

Future applications in nuclear medicine?

- diagnostic

  new developments over next 20 years?

- therapeutic

  new developments over next 20 years?

If we answer the above question for nuclear medicine, we define our needs for nuclear data measurements and evaluations over both the intermediate- and longer-term timescales

Participants

Marie-Martine Bé	Laboratoire National Henri Becquerel, France
Brett Carlson	Instituto Tecnológico de Aeronáutica (ITA), Brazil
Filip Kondev	Argonne National Laboratory, USA
Ondrej Lebeda	Czech Academy of Sciences, Czech Republic
Alan Nichols	University of Surrey, UK [Rapporteur]
Syed Qaim	Forschungszentrum Jülich, Germany [Chairman]
Deon Steyn	iThemba Laboratory, South Africa
Sandor Takács	Hungarian Academy of Sciences, Hungary

Roberto Capote: IAEA Nuclear Data Section [Scientific Secretary]

Combination of reactions & decay data experts – very beneficial!

What was discussed

- **Radionuclides & Proton, and Heavy-ion therapy**
  - ✓ Diagnostic γ-ray emitters
  - ✓ β^+ emitters
  - ✓ Therapeutic β^-, X-ray and γ-ray emitters
  - ✓ Therapeutic Auger-electron emitters
  - ✓ Therapeutic α emitters

- **Nuclear Data:**
  - ✓ Cross–section production data
  - ✓ Decay data
  - ✓ Modelling?
- **Intermediate Term:**
  - ✓ 5 to 15 years → up to 2025

Presentations by participants

Nuclear Data for Medical Applications: An Overview

S.M. Qaim *(Forschungszentrum Jülich, Germany)*

- ✓ Introduction
- ✓ Significance of decay and nuclear reaction data
- ✓ Radionuclides commonly used in medicine
- ✓ Novel positron emitters
- ✓ New approaches to internal radiotherapy
- ✓ Radiation therapy (formation of activation products)
- ✓ Conclusions

Presentations by participants – cont'd

Medical Applications Over the Intermediate Term: Decay Data Requirements

A.L. Nichols (University of Surrey, UK)

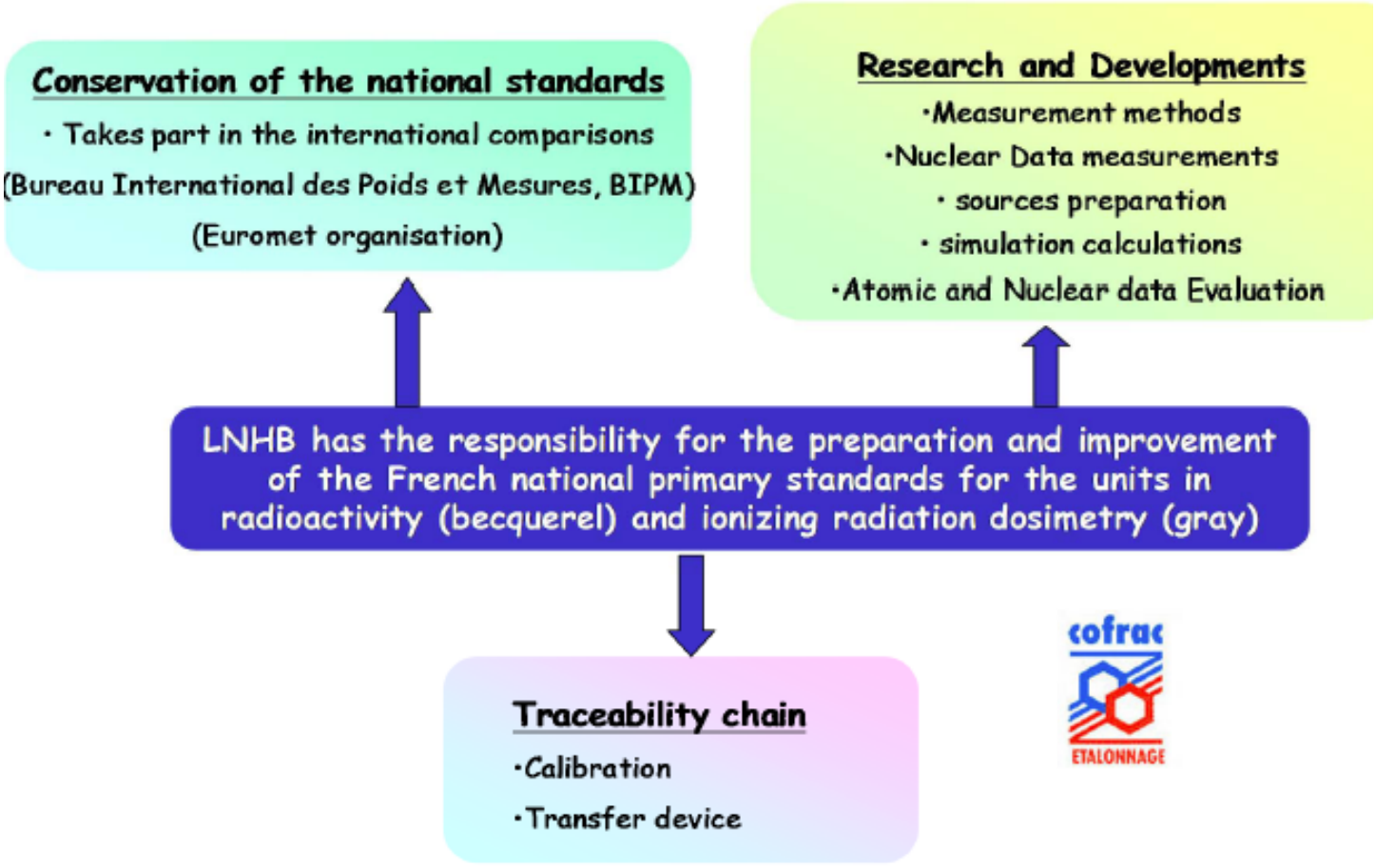
Evaluated Decay Data – Comprehensive Decay Schemes

- ✓ standards/calibrants
- ✓ actinides and heavy elements
- ✓ activation products
- ✓ fission products

review of available decay data & databases – very comprehensive

Presentations by participants – cont'd

International Links and Relevant Activities at Laboratory National Henri Becquerel (LNHB) - M.-M. Bé (CEA/LNHB, France)

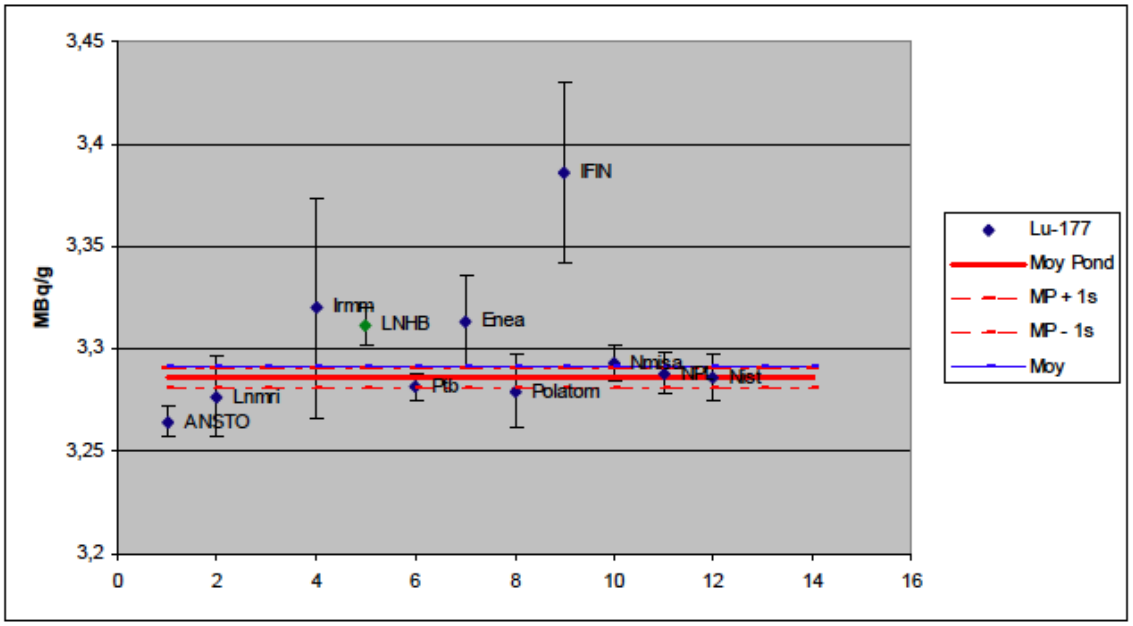


Presentations by participants – cont'd

Recent international exercises have been conducted on Lu-177 and Cu-64:

For **Lu-177**, 12 laboratories measured the activity of the same solution, results have been sent for insertion to the SIR (BIPM). Then, a Key Comparison Data Reference value will be created.

For example, an impurity of 1% in Lu-177m in a solution of Lu-177 leads to a correction of ~13 % when determining the activity in Lu-177 of this solution by using a ionization chamber.



Presentations by participants – cont'd

Nuclear Data Needs for Medical Isotope Research

F.G. Kondev (Argonne National Laboratory, USA)

- DOE funded isotope research in US
- Capabilities for isotopes research at ANL
- Nuclear Data needs – emphasis on decay data – many examples
  - ✓ importance for cross-sections measurements
  - ✓ importance for a specific medical application, e.g. imaging, diagnostic, treatment, etc.
  - ✓ data associated with atomic radiations produced in radioactive decay - Auger, Coster-Kronig & super-Coster-Kronig and other shake-off electrons
  - ✓ radionuclide impurities
- Future opportunities
  - ✓ RIB facilities – FRIB (MSU – a few slides from B. Sherrill), TRIUMF

Presentations by participants – cont'd

Neutron Data for Proton and Carbon Beam Therapy
B.V. Carlson (Instituto Tecnológico de Aeronáutica (ITA), Brazil)

Some Thoughts on Data Integrity in Stacked-Foil Experiments
G.F. Steyn, iThemba Laboratory, South Africa)

Possible Systematic Errors in Cross-section Measurements: Influence on Data Evaluations
S. Takács (INR, Hungarian Academy of Sciences, Debrecen, Hungary)

Measurement and Use of Nuclear Data for Medical Radionuclides at the Nuclear Physics Institute, Academy of Sciences of the Czech Republic
O. Lebeda (Czech Academy of Sciences, Czech Republic)

Specific Recommendations

Diagnostic γ-ray emitters

Radionuclide	Requirements	Comments
$^{99}Tc^{m}$	**^{100}Mo(p,xn), (p,α), (d,xn); (γ,n), (γ,f);** decay-data evaluated in previous CRP (IAEA-STI/PUB/1287); Auger electrons	**Accelerator production; highly-enriched ^{100}Mo (> 99%) should be investigated**
^{97}Ru	^{3}He and ^{4}He on Mo	Limited application
^{123}I	See IAEA-TECDOC-1211 and IAEA-STI/PUB/1287; Auger electrons	Several production reactions and discrepancies to be studied in planned CRP
^{147}Gd	**^{4}He on Sm; proton on Eu**	Special application in MRI + SPECT
^{203}Pb		Special application in tracer studies

β^+ emitters

Radionuclide	Requirements	Comments
^{11}C, ^{13}N, $^{14,15}O$, ^{30}P, ^{38}K	Activation cross sections for proton-induced reactions with energies up to 250 MeV	Cross sections well defined for E_p < 20 MeV → **higher energies of interest up to 250 MeV for proton therapy**
$^{34}Cl^m$	Cross-section measurements and evaluations	Low priority
^{43}Sc	**Cross-section measurements and evaluations**	Good positron-decay characteristics, but difficult to produce
^{45}Ti, ^{48}V, ^{49}Cr, ^{90}Nb	**Cross-section measurements and evaluations**	Potentially important for radioimmunotherapy
$^{51,52}Mn$	**Cross-section measurements evaluations**	Special application in MRI + PET
^{52}Fe, ^{55}Co, ^{61}Cu, $^{110}In^m$	**Cross-section evaluations**	Several novel applications
^{57}Ni, ^{72}As, ^{73}Se, $^{94}Tc^m$	**Cross-section measurements and evaluations; β^+ and X-ray emission probabilities**	Decay-data evaluation in planned CRP

β^+ emitters (continued)

Radionuclide	Requirements	Comments
^{64}Cu	Cross sections -see previous CRP (IAEA Technical Reports Series No. 473)	Important β^+ emitter, especially for radioimmunotherapy
^{66}Ga	**Cross-section measurements and evaluations; β^+ and X-ray emission probabilities**	Decay-data evaluation in planned CRP
^{68}Ga	**Cross-section measurements and evaluations**	Direct production, as well as ^{68}Ge/^{68}Ga generator route
^{75}Br, ^{77}Kr	Cross-section measurements and evaluations; β^+ and X-ray emission probabilities	Limited application
^{76}Br, ^{89}Zr	**Cross-section measurements and evaluations; β^+ and X-ray emission probabilities**	Decay-data evaluation in planned CRP
^{81}Rb, ^{82}Rb^m, ^{83}Sr,	Cross-section measurements and evaluations; β^+ and X-ray emission probabilities	Limited application
^{86}Y	**Cross-section evaluations; β^+ and X-ray emission probabilities**	**Important positron emitter for quantification of dosimetry calculations**; decay-data evaluation in planned CRP

β^+ emitters (continued)

Radionuclide	Requirements	Comments
^{95}Ru	^{3}He and ^{4}He beam cross-section measurements and evaluations	Limited application; many gamma rays, together with ~14% β^+ emission
^{120}I^{g}	**Cross-section evaluations; β^+ and X-ray emission probabilities**	Decay-data evaluation in planned CRP
^{121}I	Cross-section measurements and evaluations	Borderline – longer-term consideration (easier to produce than ^{120}I); many gamma rays, together with ~11% β^+ emission
^{124}I	Cross sections - see previous CRP (IAEA Technical Reports Series No. 473)	Important positron emitter for quantification of dosimetry calculations
^{152}Tb	**Cross-section measurements and evaluations**	Potentially useful as lanthanide-based positron emitter

β^+ emitters (continued): generators

Radionuclide	Requirements	Comments
$^{44}Ti/^{44}Sc$	**Cross-section measurements and evaluations; evaluation of parent $T_{1/2}$**	Long-lived parent ($T_{1/2}$ of 60 y); difficult to produce
$^{52}Fe/^{52}Mn^{m}$	**Cross-section and decay-data measurements and evaluations**	Special application in MRI + PET
$^{62}Zn/^{62}Cu$	**Cross-section measurements and evaluations; β^+ and X-ray emission probabilities**	Decay-data evaluation in planned CRP
$^{68}Ge/^{68}Ga$, $^{82}Sr/^{82}Rb$	**Cross-section measurements and evaluations**	**Well-established systems, but databases inadequate**
$^{72}Se/^{72}As$	**Cross-section measurements and evaluations; β^+ and X-ray emission probabilities**	Decay-data evaluation in planned CRP
$^{140}Nd/^{140}Pr$	**Cross-section measurements and evaluations; Auger-electron and other low-energy electron data for ^{140}Nd microdosimetry**	Radiotherapy + PET; parent ^{140}Nd (EC) to operate as therapeutic radionuclide, while ^{140}Pr is positron emitter (*in-vivo* generator)

Therapeutic β^-, X-ray and γ-ray emitters

Radionuclide	Requirements	Comments
^{47}Sc	Cross-section measurements and evaluations	Low-energy β^- emitter
^{67}Cu	Cross sections – see previous CRP (IAEA Technical Reports Series No. 473); decay-data measurements and evaluation, particularly g.s. to g.s. transition	Important radionuclide – emission of low-energy β^- particles, and preparation of organometallic complexes
^{103}Pd	Cross sections – see previous CRP (IAEA Technical Reports Series No. 473); decay-data discrepancies – measurements and evaluation; Auger electrons	Decay-data evaluation in planned CRP
^{131}Cs	Cross-section measurements and evaluations	X-ray emitter
^{131}Ba	Cross-section measurements and evaluations; decay-data evaluation	X-ray emitter
^{161}Tb	^{160}Gd(n,γ)^{161}Gd(β^-)^{161}Tb: decay-data measurements and evaluation	Low-energy β^- emitter

Therapeutic β^-, X-ray and γ-ray emitters (continued)

Radionuclide	Requirements	Comments
^{166}Ho	Cross sections and decay data – see previous CRP (IAEA Technical Reports Series No. 473 and IAEA-STI/PUB/1287); require cross-section measurements and evaluation for ^{164}Dy(2n,γ)^{166}Dy(β^-)^{166}Ho	High-flux reactor required for double-neutron capture
^{169}Er	Cross-section measurements and evaluations, including spallation beam cross sections; decay-data measurements and evaluation	Low-energy β^- emitter
^{175}Yb	Cross-section measurements and evaluations for charged-particle reactions; decay-data measurements and evaluation	Low-energy β^- emitter
^{191}Os /^{191}Ir^m	Cross-section measurements and evaluations	Low-energy β^- emitter for radiotherapy + SPECT; potential *in-vivo* generator
^{191}Pt /^{191}Ir^m	Cross-section and decay-data measurements and evaluations	X-ray emitter; potential *in-vivo* generator

Therapeutic Auger-electron emitters

Radionuclide	Requirements	Comments
^{67}Ga, ^{111}In	Cross sections evaluated in two previous CRPs (IAEA-TECDOC-1211 (^{67}Ga and ^{111}In), and IAEA Technical Reports Series No. 473 (^{67}Ga)); Auger electrons may become an issue	Both ^{67}Ga and ^{111}In finding increased application in internal radiotherapy
^{71}Ge	**Cross-section measurements and evaluations**; Auger electrons may become an issue	Half-life is rather long at 11.4 d
^{77}Br	**Cross-section evaluations**; Auger electrons may become an issue	
^{99}Tc^{m}	**Auger-electron (E_e < 25 keV) and other low-energy electron (E_e < 1 keV) data for microdosimetry**; decay-data evaluated in previous CRP (IAEA-STI/PUB/1287); **further needs for cross-section data will arise if produced by charged-particle reactions**	Regularly used for diagnosis, but also increased application in therapeutics
^{103}Pd	Cross sections evaluated in previous CRP (IAEA-TECDOC-1211); **decay-data measurements and evaluation**	Decay-data evaluation in planned CRP

Therapeutic Auger-electron emitters (continued)

Radionuclide	Requirements	Comments
^{123}I	See IAEA-TECDOC-1211 and IAEA-STI/PUB/1287; Auger electrons	Regularly used for diagnosis, but also increased application in therapeutics; several production reactions and discrepancies to be studied in planned CRP
^{140}Nd	Cross-section evaluations of several reactions; Auger electrons may become an issue	Auger and EC decay; *in-vivo* generator (^{140}Pr) – see previous table (β^+ emitters: generators)
^{178}Ta	^{176}Hf(α,2n)^{178}W(EC)^{178}Ta; Auger electrons may become an issue	Auger and EC decay; *in-vivo* generator (^{178}W)
^{193}Pt ^{m}, ^{195}Pt ^{m}	Cross-section measurements and evaluations; Auger electrons may become an issue	Large number of Auger electrons emitted
^{197}Hg	Cross-section and decay-data measurements and evaluations; Auger electrons may become an issue	

Therapeutic α emitters

Radionuclide	Requirements	Comments
^{149}Tb	**Cross-section measurements and evaluations of spallation and heavy-ion beam reactions**	**Emission of low-energy alpha particles (< 4 MeV) – potentially useful for special applications**
^{211}At/^{211}Po	Cross sections and decay data evaluated in previous CRPs (IAEA Technical Reports Series No. 473, and "Updated Actinide Decay Data Library (to be published))	Well-established therapeutic radionuclide
^{225}Ac/^{213}Bi	**Lack of cross-section data at higher energies for spallation reaction on ^{232}Th**; decay chain evaluated in previous CRP ("Updated Actinide Decay Data Library" (to be published))	**Potentially important therapeutic radionuclide**
^{227}Ac/^{223}Ra	**Inadequate cross-section data for ^{232}Th(p,x) production of ^{227}Ac - measurements and evaluation**; ^{223}Ra decay data evaluated in previous CRP ("Updated Actinide Decay Data Library" (to be published))	Impurity in ^{225}Ac production
^{230}U/^{226}Th	Cross-section studies within planned CRP; **decay-data evaluations of α-decay chain**	Papers containing new decay-data measurements presented at ICRM2011 conference

Intermediate future

- Planned IAEA-NDS CRP dedicated to cross sections and decay data for medical applications is based on:

✓ **High-Precision Beta-Intensity Measurements and Evaluations for Specific PET Radioisotopes** (see IAEA report INDC(NDS)-0535, 2008)

✓ **Improvements in Charged-Particle Monitor Reactions and Nuclear Data for Medical Isotope Production** (see IAEA report INDC(NDS)-0591, 2011)

- **Monitor reactions:** ^{22,24}Na, ^{46}Sc, ^{56,58}Co, ^{62,63,65}Zn, ^{96}Tc^{m+g}
- **Reactions for diagnostic γ emitters:** ^{99}Tc^{m}, ^{111}In, ^{123}I (^{123}Cs, ^{123}Xe, ^{121}I production)
- **Reactions for novel β$^+$ emitters:** ^{52}Fe, ^{55}Co, ^{61}Cu, ^{66,68}Ga, ^{72}As, ^{73}Se, ^{76}Br, ^{86}Y, ^{89}Zr, ^{94}Tc^{m}, ^{110}In^{m}, ^{120}I
- **Reactions for generators:** ^{62}Zn/^{62}Cu, ^{68}Ge/^{68}Ga, ^{72}Se/^{72}As, ^{82}Sr/^{82}Rb
- **Reactions for therapeutic isotopes:**
  - α emitters – ^{225}Ra and ^{225}Ac production (→ ^{213}Bi); ^{227}Ac impurity
  - electron and X-ray emitters – ^{131}Cs (also ^{131}Ba production)

✓ **Decay data evaluations:** ^{61}Cu, ^{62,63}Zn, ^{66}Ga, ^{72}As, ^{73}Se, ^{76}Br, ^{86}Y, ^{89}Zr, ^{94}Tc^{m}, ^{103}Pd, ^{120}I

Longer terms

- Increased dynamic and quantitative positron tomography (PET) coupled with X-ray tomography (CT) and magnetic resonance imaging (MRI) for organ imaging
- Assessment of improved internal radiotherapy:
  - ✓ PET and therapy involving radioimmuno reactions
  - ✓ Auger-electron and α-particle therapy at the cellular level
- Positron emitters and therapeutic radionuclides – long-term possibilities:
  - ✓ metallic-based positron emitters (e.g., Ti, Ga, Cu radionuclides) → developments in organometallic-complex chemistry
  - ✓ improved microdosimetry → requirement to better characterise suitable low-energy Auger-electron emitters