α, β+, γ and Auger-electron Decay Data in Nuclear Medicine – Experimental Determination, Status and Deficiencies Part II

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α, β⁺, γ and Auger-electron Decay Data in Nuclear Medicine – Experimental Determination, Status and Deficiencies Part II

Alan Nichols

Department of Physics, University of Surrey, Guildford, UK
Manipal University, Madhav Nagar, Karnataka, India

1 October 2013

Workshop on Nuclear Data for Science and Technology: Medical Applications
ICTP, Trieste, Italy, 30 September – 4 October 2013
Objectives: improve data for medical radioisotope production and patient dose delivery calculations in radiotherapy

Beneficiaries: medical physicists, radioisotope producers, researchers …

Rationale: Cancer therapy

Diagnosis

Nuclear Data for Medical Applications

Alan Nichols

ICTP, Trieste, Italy, 30 September – 4 October 2013
Production of radioisotopes for medical diagnosis and therapy
Radiotherapy: photons, electrons, protons and heavy ions
Brachytherapy combines radiotherapy with monoclonal antibodies
Dosimetry and radiation safety
Radiation transport data
Atomic and Nuclear Data

Nuclear structure and decay data

→ nuclear energy levels, half-lives and radioactive decay ($\alpha$, $\beta$, $\gamma$)

  ENSDF
  MIRD
  DDEP

Atomic decay data

→ X-rays, Auger electrons
β⁻ decay of $^{137}$Cs
**β⁻ and β⁺ decay**

**β⁻ and β⁺ spectra:**
- β emissions are NOT discrete – even reasonably simple β spectra can be difficult if not impossible to analyse so as to quantify individual β transitions
- therefore, proposed decay schemes are commonly derived from measured γ and conversion-electron energies and emission probabilities
- balance population-depopulation of nuclear levels by total (γ + ce) transitions to provide the means of calculating β⁻ emission probabilities and (EC + β⁺) transition probabilities by difference
β− and β+ decay

β− and β+ spectra:
- (EC + β+) transitions manipulated further to determine EC and β+ components of their total (EC + β+) transition probability to each specific nuclear level
- EC-to-positron ratios adopted from relevant tabulations, e.g.
  N.B. Gove, M.J. Martin, Nuclear Data Tables, 10 (1971) 205-317
- would benefit from direct (and accurate) $P_{β+}$ measurements, despite inherent difficulties
Auger emitters and related ND needs

Auger, Coster-Kronig and super-Coster-Kronig
✓ low-energy (10 eV–10 keV) electrons – short range (few nm to 1 μm)
✓ commonly emitted by radionuclides that decay by EC, CE or IT

INVITED COMMENTARY

Cancer Therapy with Auger Electrons: Are We Almost There?

✓ high toxicity – highly localized energy deposition in a small volume
✓ availability of many radionuclides with a wide range of physical half-lives
✓ emission of gamma rays - useful for imaging
more than 100 Auger emitters
most popular: $^{99}$Tcm, $^{111}$In, $^{123,125}$I, $^{67}$Ga, $^{193}$Pt
new and emerging: $^{117,119}$Sb, $^{165}$Er
Regaud and Lacassagne (1927)
“The ideal agent for cancer therapy would consist of heavy elements capable of emitting radiations of molecular dimensions, which could be administered to the organism and selectively fixed in the protoplasm of cells one seeks to destroy.”

(Technical terms and concepts related to medical applications of Auger electrons.)

Targeted tumor therapy

Auger electrons
β particles
α particles

(Courtesy of Thomas Tunningley, ANU.)
Medical applications - Auger electrons

Regaud and Lacassagne (1927)
“The ideal agent for cancer therapy would consist of heavy elements capable of emitting radiations of molecular dimensions, which could be administered to the organism and selectively fixed in the protoplasm of cells one seeks to destroy.”

Targeted tumor therapy

Biological effect:
Linear energy transfer (LET), keV/μm

(Courtesy of Thomas Tunningley, ANU).
Regaud and Lacassagne (1927)

“The ideal agent for cancer therapy would consist of heavy elements capable of emitting radiations of molecular dimensions, which could be administered to the organism and selectively fixed in the protoplasm of cells one seeks to destroy.”

22-26 August 2011

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

A.L. Nichols, et al., IAEA report INDC(NDS)-0596, September 2011

Auger emitters: $^{67}$Ga, $^{71}$Ge, $^{77}$Br, $^{99m}$Tc, $^{103}$Pd, $^{111}$In, $^{123}$I, $^{125}$I, $^{140}$Nd, $^{178}$Ta, $^{193}$Pt, $^{195m}$Pt, $^{197}$Hg

Targeted tumor therapy

(Courtesy of Thomas Tuningley, ANU)
Atomic radiations - Basic concepts

**X-ray emission**

- $E_{X K \alpha 2} = E_K - E_{L2}$
- Kα2 X-ray
- 1 secondary vacancy

**Auger-electron**

- $E_{KL2L3} = E_K - E_{L2} - E_{L3}^{L2}$
- K L2 L3 Auger-electron
- 2 new secondary vacancies
Atomic radiations - Basic concepts

X-ray emission

\[ E_{X\alpha_2} = E_K - E_{L2} \]

\( K\alpha_2 \) X-ray
1 secondary vacancy

Coster-Kronig electron

\[ E_{L1L2M1} = E_{L1} - E_{L2} - E_{M1}^{L2} \]

L1 L2 M1 Coster-Kronig transition
2 new secondary vacancies

Initial vacancy

X-ray photon
Atomic relaxation and vacancy transfer

Vacancy cascade in Xe

- Full relaxation of an initial inner shell vacancy creates vacancy cascade involving X-ray (radiative) and Auger as well as Coster-Kronig (non-radiative) transitions
- Many possible cascades for a single initial vacancy
- Typical relaxation time \( \sim 10^{-15} \) seconds
- Many vacancy cascades following a single ionisation event

Vacancies on the inner-shell can be produced by:
- electron impact
- photo ionization
- ion-atom collision
- internal conversion
- electron capture
- secondary processes accompanying β-decay or electron capture

Vacancy cascade in Xe

X-rays and Auger electrons are an integral part of the radiations emitted in nuclear decay.

Atomic radiations are important for radioisotope applications (medical physics, nuclear astrophysics, nuclear engineering).

ENSDF: atomic radiations are not included in ENSDF.
## Existing calculations

### Auger electron yield per nuclear decay

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{99}$Tcm (6.007 h)</td>
<td>0.122</td>
<td>0.13</td>
<td>4.363</td>
<td>4.0</td>
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<td>2.5</td>
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<tr>
<td>$^{111}$In (2.805 d)</td>
<td>1.136</td>
<td>1.16</td>
<td>7.215</td>
<td>14.7</td>
<td>6.05</td>
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<tr>
<td>$^{123}$I (13.22 h)</td>
<td>1.064</td>
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<td>13.71</td>
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<td></td>
<td>6.4</td>
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<td>$^{125}$I (59.4 d)</td>
<td>1.77</td>
<td>1.78</td>
<td>23.0</td>
<td>24.9</td>
<td>15.3</td>
<td>12.2</td>
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<tr>
<td>$^{201}$Tl (3.04 d)</td>
<td>0.773</td>
<td>0.614</td>
<td>20.9</td>
<td>36.9</td>
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<td></td>
</tr>
</tbody>
</table>

### Vacancy propagation

<table>
<thead>
<tr>
<th></th>
<th>Deterministic</th>
<th>Deterministic</th>
<th>Deterministic (+++)</th>
<th>Monte Carlo with charge neutralization</th>
<th>Monte Carlo</th>
<th>Monte Carlo</th>
</tr>
</thead>
</table>

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Tibor Kibedi and Alan Nichols

ICTP, Trieste, Italy, 30 September – 4 October 2013
Existing programs

Common problems/limitations:

- **Neutral atom binding energies** are sometimes used for atoms with vacancies, i.e. for ions
- **Single initial vacancy** is considered. Secondary vacancies are ignored
- **Atomic radiations only** from primary vacancies on the K and L shell
- **Limited information on sub-shell rates**
- **Auger electrons below ~ 1 keV** are often omitted
BrIccEmis – Monte Carlo approach for vacancy creation and propagation

- **Initial state:** neutral isolated atom
- **Nuclear structure data:** from nuclear decay scheme evaluation (e.g. ENSDF)
- **Electron capture (EC) rates:** Schönfeld (1998Sc28)
- **Internal conversion coefficients (ICC):** BrIcc (2008Ki07)
- **Auger and X-ray transition rates:** EADL (1991 Perkins)

  Calculated for single vacancies!

- **Auger and X-ray transition energies:** RAINE (2002Ba85)

  Calculated for actual electronic configuration!

- **Vacancy creation and relaxation from EC and IC:** treated independently

- **Ab initio treatment of the vacancy propagation:**
  - Transition energies and rates evaluated on the spot
  - Propagation terminated once the vacancy reaches the valence shell
Reads the ENSDF file, evaluates absolute decay intensities of EC, GAMMA, CE and PAIR transitions

Simulates a large number events: 100k-10M radioactive decays followed by atomic relaxation

Electron configurations and binding energies stored in memory (and saved on disk). New configurations only calculated if needed

($^{55}$Fe: 15 k, $^{201}$Tl: 1300 k)

Emitted atomic radiations stored on disk (Gb files)

Separate files for X-rays and Auger electrons

Smaller programs to sort/project energy spectra, and produce detailed reports
$^{111}\text{In EC decay – vacancy propagation}$

$^{111}\text{In EC & IC decay}$

Initial vacancy creation
$^{99}\text{Tc}^m$ atomic radiations

$Z=43$ (Tc, Technetium)
$\gamma$-energy: 2.1726 keV

Data Sets: BrIccFO

<table>
<thead>
<tr>
<th>Shell</th>
<th>E(ce)</th>
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<tbody>
<tr>
<td>Tot</td>
<td>1.370E10</td>
<td>(20)</td>
</tr>
<tr>
<td>M1</td>
<td>1.63</td>
<td>2.26E6 (4)</td>
</tr>
<tr>
<td>M2</td>
<td>1.73</td>
<td>3.37E9 (5)</td>
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<tr>
<td>M3</td>
<td>1.75</td>
<td>5.98E9 (9)</td>
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<td>M4</td>
<td>1.92</td>
<td>1.100E9 (16)</td>
</tr>
<tr>
<td>M5</td>
<td>1.92</td>
<td>1.655E9 (24)</td>
</tr>
<tr>
<td>M-tot</td>
<td>1.78</td>
<td>1.211E10 (17)</td>
</tr>
<tr>
<td>N1</td>
<td>2.10</td>
<td>5.00E5 (7)</td>
</tr>
<tr>
<td>N2</td>
<td>2.13</td>
<td>4.92E8 (7)</td>
</tr>
<tr>
<td>N3</td>
<td>2.14</td>
<td>8.77E8 (13)</td>
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<tr>
<td>N4</td>
<td>2.17</td>
<td>9.11E7 (13)</td>
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<td>N5</td>
<td>2.17</td>
<td>1.350E8 (19)</td>
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<td>N-tot</td>
<td>2.14</td>
<td>1.596E9 (23)</td>
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<tr>
<td>O1</td>
<td>2.17</td>
<td>3.49E4 (5)</td>
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<tr>
<td>O-tot</td>
<td>2.17</td>
<td>3.49E4 (5)</td>
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</tbody>
</table>

Tibor Kibèdi and Alan Nichols

ICTP, Trieste, Italy, 30 September – 4 October 2013
### $^{99}\text{Tc}^m$ atomic radiations – X-rays

<table>
<thead>
<tr>
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<th>BrLccEmis</th>
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<tr>
<td>$K\alpha_1$</td>
<td>$18.3672$</td>
<td>$18.421$</td>
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<td>$4.21E-2$</td>
<td>$4.05E-2$</td>
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<td>$K\alpha_2$</td>
<td>$18.251$</td>
<td>$18.302$</td>
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<td>$2.22E-2$</td>
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<td>$K\beta$</td>
<td>$20.677$</td>
<td>$20.729$</td>
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<td>$1.30E-2$</td>
<td>$1.18E-2$</td>
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<td>$L$</td>
<td>$[2.134 - 3.002]$</td>
<td>$2.466$</td>
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<td></td>
<td>$4.82E-3$</td>
<td>$4.72E-3$</td>
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<tr>
<td>$M$</td>
<td>$0.263$</td>
<td>$7.83E-4$</td>
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<td>$N$</td>
<td>$0.047$</td>
<td>$8.73E-1$</td>
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<td>BrlccEmis</td>
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<tr>
<td>KLL</td>
<td>[14.86:15.58]</td>
<td>15.37</td>
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<tr>
<td></td>
<td>(1.49E-2)</td>
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<td>KLX</td>
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<td>17.85</td>
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<td>(2.79E-3)</td>
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<td>KXY</td>
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<td></td>
<td>(2.8E-4)</td>
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<td>K-total</td>
<td>(2.15E-2)</td>
<td>16.15</td>
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<td>(2.08E-2)</td>
<td>(2.08E-2)</td>
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<td>CK LLM</td>
<td>(2.08E-2)</td>
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<td>CK LLX</td>
<td>0.144</td>
<td>(9.48E-3)</td>
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<tr>
<td>LMM</td>
<td>2.016</td>
<td>(9.02E-2)</td>
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<td>LMX</td>
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<td>(1.41E-2)</td>
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<tr>
<td>LXY</td>
<td>2.654</td>
<td>(6.07E-4)</td>
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<tr>
<td>L-total</td>
<td>[1.6:2.9]</td>
<td>1.765</td>
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<tr>
<td></td>
<td>(1.089E-1)</td>
<td>(1.24E-1)</td>
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</tbody>
</table>
### $^{99}$Tc$^m$ Atomic Radiations – Auger Electrons

<table>
<thead>
<tr>
<th></th>
<th>DDEP</th>
<th>Br\textsubscript{1ccEmis}</th>
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<tbody>
<tr>
<td>CK MMX</td>
<td></td>
<td>0.104</td>
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<tr>
<td></td>
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<td>$7.10E-1$</td>
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<tr>
<td>MXY</td>
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<td>0.170</td>
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<tr>
<td></td>
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<td>$1.10E+0$</td>
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<tr>
<td>Super CK NNN</td>
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<td>0.014</td>
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<tr>
<td></td>
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<td>$5.36E-1$</td>
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<tr>
<td>CK NNX</td>
<td></td>
<td>0.012</td>
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<tr>
<td></td>
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<td>$8.45E-1$</td>
</tr>
<tr>
<td>Total yield Auger electron per nuclear decay</td>
<td>$0.13$</td>
<td>$3.37$</td>
</tr>
</tbody>
</table>

~95% below 500 eV
KLL-Auger spectrum of $^{111}$Cd from EC decay of $^{111}$In

$^{111}$In(EC)$^{111}$Cd

Counts / $6 \times 15$ s

Electron energy (eV)

$^{1}$S$_0$, $^{3}$P$_0$, $^{1}$P$_1$, $^{3}$P$_1$, $^{3}$P$_2$, $^{1}$D$_2$, $^{1}$L$_1$, $^{3}$L$_3$, $^{1}$L$_2$, $^{3}$L$_2$, $^{3}$L$_3$
KMM-, KMN- and KNN-Auger spectrum of $^{111}$Cd from EC decay of $^{111}$In
$^{111}$In EC decay – experiment vs calculation


- ESCA; FWHM = 4 eV
- Calculations normalized to the strongest experimental line
New model: $^{55}$Fe EC decay

- Primary vacancies from BrIcc (for CE) and EC (for electron capture)
- Binding energies calculated using RAINE code for electron configurations of a neutral atom or an ion with single or multiple vacancies
- Auger and CK transition rates calculated using non-relativistic perturbation theory with screened hydrogen wave functions (simple general formalism for all shells and transitions)
- Partially Defrosted Orbitals: calculations for all electronic configurations (complete treatment), but with single-vacancy transition rates
Medical Internal Radiation Dose (MIRD)


2. Access software at:
   www.nndc.bnl.gov/mird/
   www-nds.iaea.org/medportal/
# Medical Internal Radiation Dose (MIRD)

**MIRD dose rate data for $^{18}$F as determined from ENSDF decay data**

<table>
<thead>
<tr>
<th>Radiation</th>
<th>$P_i$ (Bq-s)$^{-1}$</th>
<th>Energy (MeV)</th>
<th>$P_i \times E_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^+$</td>
<td>$9.67 \times 10^{-01}$</td>
<td>$2.498 \times 10^{-01}$</td>
<td>$2.42 \times 10^{-01}$</td>
</tr>
<tr>
<td>$\gamma^\pm$</td>
<td>$1.93$</td>
<td>$5.110 \times 10^{-01}$</td>
<td>$9.89 \times 10^{-01}$</td>
</tr>
<tr>
<td>K X-ray</td>
<td>$1.80 \times 10^{-04}$</td>
<td>$5.249 \times 10^{-04}$</td>
<td>$9.42 \times 10^{-08}$</td>
</tr>
<tr>
<td>K X-ray</td>
<td>$4.74 \times 10^{-12}$</td>
<td>$5.000 \times 10^{-04}$</td>
<td>$2.37 \times 10^{-15}$</td>
</tr>
<tr>
<td>Auger-K</td>
<td>$3.07 \times 10^{-02}$</td>
<td>$5.200 \times 10^{-04}$</td>
<td>$1.60 \times 10^{-05}$</td>
</tr>
</tbody>
</table>

Listed $X$, $\gamma$ and $\gamma^\pm$ radiations $9.89 \times 10^{-01}$

Listed $\beta$, $\alpha$ and Auger radiations $2.42 \times 10^{-01}$

Listed radiations $1.23$  

* Average energy (MeV).
Medical Internal Radiation Dose (MIRD)

MIRD dose rate data for $^{213}$Bi as determined from ENSDF decay data

<table>
<thead>
<tr>
<th>Radiation</th>
<th>$P_i$ (Bq-s)$^{-1}$</th>
<th>Energy (MeV)</th>
<th>$P_i \times E_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$</td>
<td>$1.55 \times 10^{-03}$</td>
<td>5.549</td>
<td>$8.58 \times 10^{-03}$</td>
</tr>
<tr>
<td>$\alpha$ recoil</td>
<td>$1.55 \times 10^{-03}$</td>
<td>$1.053 \times 10^{-01}$</td>
<td>$1.63 \times 10^{-04}$</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>$1.94 \times 10^{-02}$</td>
<td>5.869</td>
<td>$1.14 \times 10^{-01}$</td>
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<tr>
<td>$\alpha$ recoil</td>
<td>$1.94 \times 10^{-02}$</td>
<td>$1.114 \times 10^{-01}$</td>
<td>$2.16 \times 10^{-03}$</td>
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<tr>
<td>$\gamma_1$</td>
<td>$1.27 \times 10^{-04}$</td>
<td>$8.680 \times 10^{-01}$</td>
<td>$1.11 \times 10^{-04}$</td>
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<tr>
<td>$\beta^-_3$</td>
<td>$5.86 \times 10^{-03}$</td>
<td>$9.080 \times 10^{-02}$*</td>
<td>$5.32 \times 10^{-04}$</td>
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<td>$\beta^-_8$</td>
<td>$3.07 \times 10^{-01}$</td>
<td>$3.204 \times 10^{-01}$*</td>
<td>$9.85 \times 10^{-02}$</td>
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<td>$\beta^-_9$</td>
<td>$2.29 \times 10^{-03}$</td>
<td>$3.768 \times 10^{-01}$*</td>
<td>$8.62 \times 10^{-04}$</td>
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<tr>
<td>$\beta^-_{10}$</td>
<td>$6.58 \times 10^{-01}$</td>
<td>$4.922 \times 10^{-01}$*</td>
<td>$3.24 \times 10^{-01}$</td>
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<tr>
<td>$\gamma_1$</td>
<td>$4.29 \times 10^{-03}$</td>
<td>$2.928 \times 10^{-01}$</td>
<td>$1.26 \times 10^{-03}$</td>
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<tr>
<td>$\gamma_{17}$</td>
<td>$5.20 \times 10^{-04}$</td>
<td>1.119</td>
<td>$5.82 \times 10^{-04}$</td>
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<tr>
<td>$K_{\alpha 1}$ X-ray</td>
<td>$1.83 \times 10^{-02}$</td>
<td>$7.929 \times 10^{-02}$</td>
<td>$1.45 \times 10^{-03}$</td>
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<tr>
<td>$K_{\alpha 2}$ X-ray</td>
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<td>$7.686 \times 10^{-02}$</td>
<td>$8.45 \times 10^{-04}$</td>
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<tr>
<td>$K_{\beta}$ X-ray</td>
<td>$8.27 \times 10^{-03}$</td>
<td>$8.980 \times 10^{-02}$*</td>
<td>$7.43 \times 10^{-04}$</td>
</tr>
<tr>
<td>L X-ray</td>
<td>$1.55 \times 10^{-02}$</td>
<td>$1.110 \times 10^{-02}$*</td>
<td>$1.72 \times 10^{-04}$</td>
</tr>
</tbody>
</table>

Listed X, $\gamma$ and $\gamma^\pm$ radiations

Omitted X, $\gamma$, and $\gamma^\pm$ radiations** 1.22×10$^{-02}$

Listed $\beta$, $\gamma$, and Auger radiations 4.24×10$^{-01}$

Omitted $\beta$, $\gamma$, and Auger radiations** 7.74×10$^{-04}$

Listed $\alpha$ radiations 1.22×10$^{-01}$

Listed radiations 5.58×10$^{-01}$

Omitted radiations** 7.89×10$^{-04}$

* Average energy (MeV).

Each omitted transition contributes < 0.100% to $\Sigma(P_i \times E_i)$. ICTP, Trieste, Italy, 30 September – 4 October 2013
Nuclear Data Needs for Medical Applications:
Cross Sections and Decay Data

Relevant recent past:

Immediate past and future:
Cross sections and decay data – one further IAEA-NDS CRP launched in late 2012 on the basis of
- 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)
High-precision $\beta^+$-intensity Measurements and Evaluations for Specific PET Radioisotopes

Consultants’ Meeting, IAEA Headquarters, Vienna, Austria
3-5 September 2008, IAEA report INDC(NDS)-0535

Tadashi Nozaki  ex-RIKEN, Japan
Syed Qaim  Forschungszentrum Jülich, Germany  [Chairman]
Deon Steyn  iThemba Laboratory, South Africa
Stephen Waters  ex-Cyclotron Unit, Hammersmith Hospital, UK
Roberto Capote  IAEA Nuclear Data Section  [Scientific Secretary]
Alan Nichols  IAEA Nuclear Data Section  [Rapporteur]
### Radionuclides – standard $\beta^+$ emitters

<table>
<thead>
<tr>
<th>Radionuclides</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$C, $^{13}$N, $^{15}$O, $^{18}$F</td>
<td>none - well-defined decay data</td>
</tr>
<tr>
<td>$^{68}$Ge/$^{68}$Ga, $^{82}$Sr/$^{82}$Rb</td>
<td>none - well-defined $^{68}$Ga and $^{82}$Rb decay data</td>
</tr>
</tbody>
</table>

### Radionuclides – hadron therapy

<table>
<thead>
<tr>
<th>Radionuclides</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$C, $^{14}$O, $^{17}$F, $^{18}$Ne, $^{19}$Ne</td>
<td>none – adequate decay data</td>
</tr>
</tbody>
</table>
### High-precision $\beta^+$-intensity Measurements and Evaluations for Specific PET Radioisotopes

Consultants’ Meeting, IAEA Headquarters, Vienna, Austria  
3-5 September 2008, IAEA report INDC(NDS)-0535

<table>
<thead>
<tr>
<th>Radionuclides – non-standard $\beta^+$ emitters</th>
<th>Requirements</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$t_{1/2}$</td>
</tr>
<tr>
<td>$^{57}\text{Ni}$</td>
<td>√</td>
</tr>
<tr>
<td>$^{66}\text{Ga}$, $^{72}\text{As}$, $^{73}\text{Se}$, $^{86}\text{Y}$, $^{94}\text{Tc}^m$</td>
<td>√</td>
</tr>
<tr>
<td>$^{75}\text{Br}$, $^{77}\text{Kr}$</td>
<td>√</td>
</tr>
<tr>
<td>$^{64}\text{Cu}$</td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Br}$, $^{120}\text{I}$</td>
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</tr>
<tr>
<td>$^{81}\text{Rb}$, $^{82}\text{Rb}^m$, $^{83}\text{Sr}$</td>
<td></td>
</tr>
<tr>
<td>$^{22}\text{Na}$, $^{30}\text{P}$, $^{34}\text{Cl}^m$, $^{38}\text{K}$, $^{45}\text{Ti}$, $^{48}\text{V}$, $^{49}\text{Cr}$, $^{51}\text{Mn}$, $^{52}\text{Mn}$, $^{52}\text{Mn}^m$, $^{52}\text{Fe}$, $^{55}\text{Co}$, $^{61}\text{Cu}$, $^{90}\text{Nb}$, $^{110}\text{In}^m$, $^{124}\text{I}$, $^{152}\text{Tb}$, $^{44}\text{Ti}/^{44}\text{Sc}$, $^{62}\text{Zn}/^{62}\text{Cu}$, $^{140}\text{Nd}/^{140}\text{Pr}$</td>
<td></td>
</tr>
</tbody>
</table>

- most important non-standard radionuclides for PET (2008).
- increasingly important for PET (2008).
- merit further work for potential PET applications (2008).
NUCLEAR DATA FOR CHARGED-PARTICLE MONITOR REACTIONS AND MEDICAL ISOTOPE PRODUCTION

First Research Coordination Meeting, 3-7 December 2012

IAEA Report INDC(NDS)-0630

Marie-Martine Bé Laboratoire National Henri Becquerel
Brett Carlson Instituto Tecnologico de Aeronautica,
Mazhar Hussain Government College University, Lahore
Anatoly Ignatyuk Institute for Physics and Power Engineering
Guinyun Kim Kyungpook National University, Republic of Korea
Filip Kondev Argonne National Laboratory, USA
Ondrej Lebeda Nuclear Physics Institute, Academy of Sciences
Aurelian Luca National Institute of Physics and Nuclear Engineering
Yasuki Nagai Osaka University, Japan
Haladhara Naik Bhabha Atomic Research Centre, India
Alan Nichols University of Surrey, UK
Meiring Nortier Los Alamos National Laboratory, USA
Ingo Spahn Forschungszentrum Jülich, Germany
Ferenc Tarkányi Hungarian Academy of Sciences, Hungary
Roberto Capote IAEA Nuclear Data Section
<table>
<thead>
<tr>
<th>Cross sections</th>
<th>Decay data</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>monitor reactions</td>
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</tr>
<tr>
<td>$^{27}$Al(p,x)$^{22,24}$Na</td>
<td>$^{22,24}$Na</td>
<td>re-evaluate up to 800 MeV</td>
</tr>
<tr>
<td>$^{27}$Al(d,x)$^{22,24}$Na</td>
<td>$^{22,24}$Na</td>
<td>re-evaluate</td>
</tr>
<tr>
<td>$^{27}$Al($^3$He,x)$^{22,24}$Na</td>
<td>$^{22,24}$Na</td>
<td>re-evaluate</td>
</tr>
<tr>
<td>$^{27}$Al($\alpha$,x)$^{22,24}$Na</td>
<td>$^{22,24}$Na</td>
<td>measure and re-evaluate</td>
</tr>
<tr>
<td>nat$^{Ti}$d(x)$^{46}$Sc</td>
<td>$^{46}$Sc</td>
<td>re-evaluate</td>
</tr>
<tr>
<td>nat$^{Ti}$($^3$He,x)$^{48}$V</td>
<td>$^{48}$V</td>
<td>measure and re-evaluate up to 46 MeV</td>
</tr>
<tr>
<td>nat$^{Ni}$d(x)$^{56,58}$Co</td>
<td>$^{56,58}$Co</td>
<td>measure and re-evaluate</td>
</tr>
<tr>
<td>nat$^{Cu}$p(x)$^{58}$Co</td>
<td>$^{58}$Co</td>
<td>measure and evaluate up to 100 MeV</td>
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<tr>
<td>nat$^{Cu}$(p,x)$^{62,63,65}$Zn</td>
<td>$^{62,63,65}$Zn</td>
<td>inconsistencies – measure and re-evaluate; evaluate $^{62,63}$Zn decay schemes</td>
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<tr>
<td>nat$^{Cu}$d(x)$^{62,63,65}$Zn</td>
<td>$^{62,63,65}$Zn</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>nat$^{Cu}$($\alpha$,x)$^{66,67}$Ga, $^{65}$Zn</td>
<td>$^{66,67}$Ga, $^{65}$Zn</td>
<td>measure and re-evaluate</td>
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<tr>
<td>nat$^{Mo}$p(x)$^{96}$Tc$^{g+m}$</td>
<td>$^{96}$Tc$^{g+m}$</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{61}$Cu</td>
<td>$^{61}$Cu</td>
<td>evaluate $^{61}$Cu decay scheme</td>
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<tr>
<td>Cross sections</td>
<td>Decay data</td>
<td>Additional comments</td>
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<tr>
<td>----------------</td>
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<tr>
<td>diagnostic γ emitters</td>
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</tr>
<tr>
<td>$^{90}\text{Zr}(n,p)^{90}\text{Y}_{g+m}$</td>
<td>$^{99}\text{Tc}$</td>
<td>re-evaluate</td>
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<tr>
<td>$^{100}\text{Mo}(n,2n)^{99}\text{Mo}$</td>
<td>$^{99}\text{Tc}_{g+m}$</td>
<td>evaluate; decay data - focus on Auger electrons</td>
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<tr>
<td>$^{100}\text{Mo}(p,2n)^{99}\text{Tc}_{g+m}$</td>
<td></td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{100}\text{Mo}(p,pn)^{99}\text{Mo}$</td>
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<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{100}\text{Mo}(d,3n)^{99}\text{Tc}_{g+m}$</td>
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<td>evaluate</td>
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<tr>
<td>$^{100}\text{Mo}(d,p2n)^{99}\text{Mo}$</td>
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</tr>
<tr>
<td>$^{100}\text{Mo}(\gamma,n)^{99}\text{Mo}$</td>
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<td>measure</td>
</tr>
<tr>
<td>$^{100}\text{Mo}(\gamma,f)^{99}\text{Mo}$</td>
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<td>measure</td>
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<tr>
<td>$^{64}\text{Zn}(n,p)^{67}\text{Cu}$</td>
<td>$^{67}\text{Cu}$</td>
<td>measure and evaluate; evaluate $^{67}\text{Cu}$ decay scheme</td>
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<tr>
<td>$^{67}\text{Zn}(n,p)^{64}\text{Cu}$</td>
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<td>measure and evaluate; $^{64}\text{Cu}$ impurity from $^{\text{nat}}\text{Zn}(n,p)$ reaction</td>
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<tr>
<td>$^{68}\text{Zn}(n,x)^{67}\text{Cu}$</td>
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<td>measure and evaluate</td>
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<tr>
<td>$^{68}\text{Zn}(\gamma,p)^{67}\text{Cu}$</td>
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<td>measure</td>
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<tr>
<td>$^{112}\text{Cd}(p,2n)^{111}\text{In}$</td>
<td>$^{111}\text{In}$</td>
<td>re-evaluate; decay data - focus on Auger electrons</td>
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### Cross sections

#### Diagnostic γ emitters (cont.)

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<tr>
<th>Reaction</th>
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<tr>
<td>$^{124}$Xe(p,2n)$^{123}$Cs</td>
<td>−</td>
<td>re-evaluate – $^{123}$I production</td>
</tr>
<tr>
<td>$^{124}$Xe(p,pn)$^{123}$Xe</td>
<td>−</td>
<td>re-evaluate – $^{123}$I production</td>
</tr>
<tr>
<td>$^{124}$Xe(p,x)$^{121}$I</td>
<td>−</td>
<td>evaluate – $^{123}$I production: $^{121}$I impurity from $^{124}$Xe(p,x) reaction</td>
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</table>

<table>
<thead>
<tr>
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<th>Additional comments</th>
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</thead>
<tbody>
<tr>
<td>$^{51}$V(p,n)$^{51}$Cr</td>
<td>−</td>
<td>evaluate all noteworthy production routes of $^{51}$Cr</td>
</tr>
<tr>
<td>$^{51}$Cr</td>
<td>−</td>
<td>measure and evaluate</td>
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</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Decay data</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{203}$Tl(p,2n)$^{202}$Pb$^{m}$EC$^{202}$Tl</td>
<td>−</td>
<td>re-evaluate</td>
</tr>
<tr>
<td>$^{203}$Tl(p,3n)$^{201}$Pb(EC)$^{201}$Tl</td>
<td>−</td>
<td>re-evaluate</td>
</tr>
<tr>
<td>$^{203}$Tl(p,4n)$^{200}$Pb(EC)$^{200}$Tl</td>
<td>−</td>
<td>re-evaluate</td>
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<table>
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<th>Additional comments</th>
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<tbody>
<tr>
<td>$^{nat}$W(α,x)$^{186,188}$Re</td>
<td>−</td>
<td>measure</td>
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<td>Cross sections</td>
<td>Decay data</td>
<td>Additional comments</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
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<tr>
<td>$\beta^+$ emitters</td>
<td>$^{52}\text{Fe}$</td>
<td>evaluate; evaluate $^{52}\text{Fe}$ decay scheme</td>
</tr>
<tr>
<td>$^{55}\text{Mn}(p,4n)^{52}\text{Fe}$</td>
<td>$^{52}\text{Fe}$</td>
<td>evaluate</td>
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<td>$^{nat}\text{Ni}(p,x)^{52}\text{Fe}$</td>
<td>$^{52}\text{Fe}$</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{52}\text{Cr}(^3\text{He},3n)^{52}\text{Fe}$</td>
<td>$^{52}\text{Fe}$</td>
<td>evaluate</td>
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<td>$^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$</td>
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<td>$^{54}\text{Fe}(d,n)^{55}\text{Co}$</td>
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<td>$^{56}\text{Fe}(p,2n)^{55}\text{Co}$</td>
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<td>$^{nat}\text{Fe}(p,x)^{55}\text{Co}$</td>
<td>$^{55}\text{Co}$</td>
<td>measure and evaluate</td>
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<td>$^{61}\text{Ni}(p,n)^{61}\text{Cu}$</td>
<td>$^{61}\text{Cu}$</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{64}\text{Zn}(p,\alpha)^{61}\text{Cu}$</td>
<td>$^{61}\text{Cu}$</td>
<td>measure and evaluate</td>
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<tr>
<td>$^{66}\text{Zn}(p,n)^{66}\text{Ga}$</td>
<td>$^{66}\text{Ga}$</td>
<td>evaluate; decay data - positron intensities: measurements, and $^{66}\text{Ga}$ evaluate decay scheme</td>
</tr>
<tr>
<td>$^{63}\text{Cu}(\alpha,n)^{66}\text{Ga}$</td>
<td>$^{66}\text{Ga}$</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{68}\text{Zn}(p,n)^{68}\text{Ga}$</td>
<td>$^{68}\text{Ga}$</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{65}\text{Cu}(\alpha,n)^{68}\text{Ga}$</td>
<td>$^{68}\text{Ga}$</td>
<td>evaluate</td>
</tr>
<tr>
<td>Cross sections</td>
<td>Decay data</td>
<td>Additional comments</td>
</tr>
<tr>
<td>----------------</td>
<td>------------</td>
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<tr>
<td>$\beta^+$ emitters (cont.)</td>
<td>$^{72}\text{As}$</td>
<td>measure and evaluate; decay data - positron intensities: measurements, and evaluate $^{72}\text{As}$ decay scheme</td>
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<tr>
<td>$^{nat}\text{Ge}(p,xn)^{72}\text{As}$</td>
<td>$^{72}\text{As}$</td>
<td></td>
</tr>
<tr>
<td>$^{75}\text{As}(p,3n)^{73}\text{Se}$</td>
<td>$^{73}\text{Se}$</td>
<td>measure and evaluate; decay data - positron intensities: measurements, and evaluate $^{73}\text{Se}$ decay scheme</td>
</tr>
<tr>
<td>$^{72}\text{Ge}(\alpha,3n)^{73}\text{Se}$</td>
<td>$^{73}\text{Se}$</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{76}\text{Se}(p,n)^{76}\text{Br}$</td>
<td>$^{76}\text{Br}$</td>
<td>measure and evaluate; decay data - positron intensities: measurements, and evaluate $^{76}\text{Br}$ decay scheme</td>
</tr>
<tr>
<td>$^{77}\text{Se}(p,2n)^{76}\text{Br}$</td>
<td>$^{76}\text{Br}$</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{75}\text{As}(\alpha,3n)^{76}\text{Br}$</td>
<td>$^{76}\text{Br}$</td>
<td>evaluate</td>
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<tr>
<td>$^{86}\text{Sr}(p,n)^{86}\text{Y}$</td>
<td>$^{86}\text{Y}$</td>
<td>re-evaluate; decay data - positron intensities: measurements, and evaluate $^{86}\text{Y}$ decay scheme</td>
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<tr>
<td>$^{88}\text{Sr}(p,3n)^{86}\text{Y}$</td>
<td>$^{86}\text{Y}$</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{85}\text{Rb}(\alpha,3n)^{86}\text{Y}$</td>
<td>$^{86}\text{Y}$</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{89}\text{Y}(p,n)^{89}\text{Zr}$</td>
<td>$^{89}\text{Zr}$</td>
<td>evaluate; measure and evaluate $^{89}\text{Zr}$ decay scheme</td>
</tr>
<tr>
<td>$^{89}\text{Y}(d,2n)^{89}\text{Zr}$</td>
<td>$^{89}\text{Zr}$</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{nat}\text{Y}(\alpha,x)^{89}\text{Zr}$</td>
<td>$^{89}\text{Zr}$</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>Cross sections</td>
<td>Decay data</td>
<td>Additional comments</td>
</tr>
<tr>
<td>--------------------------------</td>
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<td>---------------------------------------------------------</td>
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<tr>
<td>$\beta^+$ emitters (cont.)</td>
<td>$^{93}$Nb(p,x)$^{90}$Nb</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{89}$Y(\alpha,x)$^{90}$Nb</td>
<td>$^{94}$Mo(p,n)$^{94}$Te\textsuperscript{m}</td>
<td>measure and evaluate  $^{94}$Te\textsuperscript{m} decay scheme</td>
</tr>
<tr>
<td>$^{94}$Mo(\alpha,x)$^{94}$Te\textsuperscript{m}</td>
<td>$^{111}$Cd(p,2n)$^{110}$In\textsuperscript{m}</td>
<td>evaluate; measure and evaluate  $^{94}$Te\textsuperscript{m} decay scheme</td>
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<tr>
<td>$^{120}$Te(p,n)$^{120}$I</td>
<td>$^{122}$Te(p,3n)$^{120}$I</td>
<td>evaluate; measure and evaluate  $^{120}$I decay scheme</td>
</tr>
<tr>
<td>$^{120}$I</td>
<td>$^{64}$Cu</td>
<td>evaluate decay scheme – discrepant weak gamma emission</td>
</tr>
<tr>
<td>Cross sections</td>
<td>Decay data</td>
<td>Additional comments</td>
</tr>
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<tr>
<td><strong>β⁺ emitters: generators</strong></td>
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<tr>
<td>$^{62}\text{Zn}/^{62}\text{Cu}$ generator:</td>
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<td>PET analogue of therapeutic $^{67}\text{Cu}$</td>
</tr>
<tr>
<td>$^{63}\text{Cu}(p,2n)^{62}\text{Zn}$</td>
<td>–</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{68}\text{Ge}/^{68}\text{Ga}$ generator:</td>
<td></td>
<td>PET analogue of new/proposed therapeutic $^{67}\text{Ga}$</td>
</tr>
<tr>
<td>$^{\text{nat}}\text{Ga}(p,xn)^{68}\text{Ge}$</td>
<td>–</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{69}\text{Ga}(p,2n)^{68}\text{Ge}$</td>
<td>–</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{71}\text{Ga}(p,4n)^{68}\text{Ge}$</td>
<td>–</td>
<td>measure and evaluate</td>
</tr>
<tr>
<td>$^{72}\text{Se}/^{72}\text{As}$ generator:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{75}\text{As}(p,4n)^{72}\text{Se}$</td>
<td>–</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{\text{nat}}\text{Br}(p,x)^{72}\text{Se}$</td>
<td>–</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{82}\text{Sr}/^{82}\text{Rb}$ generator:</td>
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</tr>
<tr>
<td>$^{\text{nat}}\text{Rb}(p,xn)^{82}\text{Sr}$</td>
<td>–</td>
<td>evaluate</td>
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</table>
### 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

<table>
<thead>
<tr>
<th>Cross sections</th>
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<th>Additional comments</th>
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<td><strong>β⁺ emitters: generators</strong></td>
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<td></td>
</tr>
<tr>
<td>⁴⁴Ti/⁴⁴Sc</td>
<td>⁴⁴Ti $t_{1/2}$</td>
<td>evaluate ⁴⁴Ti half-life</td>
</tr>
<tr>
<td>⁵²Fe/⁵²Mnₘ</td>
<td>–</td>
<td>evaluate</td>
</tr>
<tr>
<td>¹¹⁰Sn/¹¹⁰Inₘ</td>
<td>–</td>
<td>evaluate; PET analogue of therapeutic ¹¹¹In and ¹¹⁴Inₘ</td>
</tr>
<tr>
<td>¹¹⁸Te/¹¹⁸Sb</td>
<td>–</td>
<td>evaluate; PET analogue of new/proposed therapeutic ¹¹⁷Sb and ¹¹⁹Sb</td>
</tr>
<tr>
<td>¹²²Xe/¹²²I</td>
<td>–</td>
<td>evaluate; PET analogue of therapeutic ¹²³I, ¹²⁵I and ¹³¹I</td>
</tr>
<tr>
<td>¹²⁸Ba/¹²⁸Cs</td>
<td>–</td>
<td>evaluate; PET analogue of new/proposed therapeutic ¹³¹Cs</td>
</tr>
<tr>
<td>¹⁴⁰Nd/¹⁴⁰Pr</td>
<td>–</td>
<td>evaluate</td>
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<td>Decay data</td>
<td>Additional comments</td>
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<tr>
<td>$^{229}$Th($\alpha$)$^{225}$Ra($\beta^-$)$^{225}$Ac($\alpha$) decay chain to $^{213}$Bi:</td>
<td>$^{230}$U decay chain</td>
<td>measurements up to 200 MeV, and evaluate measurements up to 200 MeV, and evaluate measure and re-evaluate evaluate; $^{227}$Ac ($t_1/2$ 21.8 y) long-lived contaminant of $^{225}$Ac ($t_1/2$ 10.0 d)</td>
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<td>$^{226}$Ra(p,2n)$^{225}$Ac</td>
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<td>$^{232}$Th(p,x)$^{227}$Ac</td>
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<tr>
<td>$^{230}$U($\alpha$)$^{226}$Th($\alpha$) decay chain:</td>
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<td>evaluate all decay schemes in decay chain:</td>
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<td>$^{231}$Pa(d,3n)$^{230}$U</td>
<td>$^{230}$U($\alpha$)$^{226}$Th($\alpha$)$^{222}$Ra($\alpha$)$^{218}$Rn($\alpha$)$^{214}$Po($\alpha$)$^{210}$Pb($\beta^-$) $^{210}$Bi($\beta^-$)$^{210}$Po($\alpha$)$^{206}$Pb(stable)</td>
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<td>$^{231}$Pa(p,2n)$^{230}$U</td>
<td>evaluate</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{232}$Th(p,3n)$^{230}$Pa($\beta^-$)$^{230}$U</td>
<td>$^{230}$Pa $\beta^-$ branch of only 7.8% – evaluate</td>
<td></td>
</tr>
</tbody>
</table>
### Cross sections

**electron and X-ray emitters**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Decay data</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{130}\text{Ba}(n,\gamma)^{131}\text{Ba}(\text{EC})^{131}\text{Cs}$</td>
<td>–</td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{131}\text{Xe}(p,n)^{131}\text{Cs}$</td>
<td></td>
<td>evaluate</td>
</tr>
<tr>
<td>$^{133}\text{Cs}(p,3n)^{131}\text{Ba}(\text{EC})^{131}\text{Cs}$</td>
<td></td>
<td>evaluate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Decay data</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{176}\text{Hf}(\alpha,2n)^{178}\text{W}(\text{EC})^{178}\text{Ta}$</td>
<td>$^{178}\text{Ta}$</td>
<td>measure and evaluate; decay data - focus on Auger electrons</td>
</tr>
<tr>
<td>nat$^{176}\text{Hf}(p,x)^{178}\text{Ta}$</td>
<td></td>
<td>measure and evaluate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Decay data</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>$^{103}\text{Pd}$</td>
<td>evaluate $^{103}\text{Pd}$ decay scheme (including Auger electrons)</td>
</tr>
</tbody>
</table>
Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data

Technical Meeting
IAEA Headquarters, Vienna, Austria
22-26 August 2011

Nuclear Medicine: Nuclear Data 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
Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data

Technical Meeting
IAEA Headquarters, Vienna, Austria
22-26 August 2011

Radionuclides:

Diagnostic $\gamma$-ray emitters

$\beta^+$ emitters

Therapeutic $\beta^-$, X-ray and $\gamma$-ray emitters

Therapeutic Auger-electron emitters

Therapeutic $\alpha$ emitters

Proton and heavy-ion beam therapy
Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data

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22-26 August 2011

Nuclear Data:

Cross–section production data

Decay data

Modelling?

Intermediate Term:

5 to 15 years → up to 2025
Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data

Technical Meeting
IAEA Headquarters, Vienna, Austria
22-26 August 2011

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]
Immediate past and future:

22–26 August 2011, IAEA Headquarters, Vienna, Austria

Intermediate–term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data
A.L. Nichols, S.M. Qaim and R. Capote Noy

IAEA report INDC(NDS)–0596, September 2011
## Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data

**Technical Meeting**  
IAEA Headquarters, Vienna, Austria  
22-26 August 2011

### Diagnostic γ-ray emitters

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{99}$Tc$^{m}$</td>
<td>$^{100}$Mo(p,xn), (p,α), (d,xn); (y,n), (γ,f); nuclear decay data evaluated in previous CRP (IAEA-STI/PUB/1287); Auger electrons</td>
<td>Accelerator production; highly-enriched $^{100}$Mo (&gt; 99%) should be investigated; Auger-electron studies planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{97}$Ru</td>
<td>$^{3}$He and $^{4}$He on Mo</td>
<td>Limited application</td>
</tr>
<tr>
<td>$^{123}$I</td>
<td>See IAEA-TECDOC-1211 and IAEA-STI/PUB/1287; Auger electrons</td>
<td>Several production reactions and discrepancies to be studied in planned CRP</td>
</tr>
<tr>
<td>$^{147}$Gd</td>
<td>$^{4}$He on Sm; proton on Eu</td>
<td>Special application in MRI + SPECT</td>
</tr>
<tr>
<td>$^{203}$Pb</td>
<td></td>
<td>Special application in tracer studies</td>
</tr>
</tbody>
</table>

Alan Nichols

ICTP, Trieste, Italy, 30 September – 4 October 2013
<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}\text{C}$, $^{13}\text{N}$, $^{14,15}\text{O}$, $^{30}\text{P}$, $^{38}\text{K}$</td>
<td>Activation cross sections for proton-induced reactions with energies up to 250 MeV</td>
<td>Cross sections well defined for $E_p &lt; 20$ MeV $\rightarrow$ higher energies of interest up to 250 MeV for proton therapy</td>
</tr>
<tr>
<td>$^{34}\text{Cl}^\text{m}$</td>
<td>Cross-section measurements and evaluations</td>
<td>Low priority</td>
</tr>
<tr>
<td>$^{43}\text{Sc}$</td>
<td>Cross-section measurements and evaluations</td>
<td>Good positron-decay characteristics, but difficult to produce</td>
</tr>
<tr>
<td>$^{45}\text{Ti}$, $^{48}\text{V}$, $^{49}\text{Cr}$, $^{90}\text{Nb}$</td>
<td>Cross-section measurements and evaluations</td>
<td>Potentially important for radioimmunotherapy</td>
</tr>
<tr>
<td>$^{51,52}\text{Mn}$</td>
<td>Cross-section measurements and evaluations</td>
<td>Special application in MRI + PET</td>
</tr>
<tr>
<td>$^{52}\text{Fe}$, $^{55}\text{Co}$, $^{61}\text{Cu}$, $^{110}\text{In}^\text{m}$</td>
<td>Cross-section evaluations</td>
<td>Several novel applications; $^{52}\text{Fe}$ and $^{61}\text{Cu}$ decay-data evaluations planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{57}\text{Ni}$, $^{72}\text{As}$, $^{73}\text{Se}$, $^{94}\text{Tc}^\text{m}$</td>
<td>Cross-section measurements and evaluations; $\beta^+$ and X-ray emission probabilities</td>
<td>$^{72}\text{As}$, $^{73}\text{Se}$ and $^{94}\text{Tc}^\text{m}$ decay-data evaluations planned in CRP (2012)</td>
</tr>
</tbody>
</table>

β+ emitters

ICTP, Trieste, Italy, 30 September – 4 October 2013

Alan Nichols
### β⁺ emitters (continued)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{64}$Cu</td>
<td>Cross sections - see previous CRP (<a href="https://www.iaea.org">IAEA Technical Reports Series No. 473</a>)</td>
<td>Important β⁺ emitter, especially for radioimmunotherapy; decay-data evaluation planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{66}$Ga</td>
<td>Cross-section measurements and evaluations; β⁺ and X-ray emission probabilities</td>
<td>Decay-data evaluation planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{68}$Ga</td>
<td>Cross-section measurements and evaluations</td>
<td>Direct production, as well as $^{68}$Ge/$^{68}$Ga generator route</td>
</tr>
<tr>
<td>$^{75}$Br, $^{77}$Kr</td>
<td>Cross-section measurements and evaluations; β⁺ and X-ray emission probabilities</td>
<td>Limited application</td>
</tr>
<tr>
<td>$^{76}$Br, $^{89}$Zr</td>
<td>Cross-section measurements and evaluations; β⁺ and X-ray emission probabilities</td>
<td>Decay-data evaluations planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{81}$Rb, $^{82}$Rb$^m$, $^{83}$Sr,</td>
<td>Cross-section measurements and evaluations; β⁺ and X-ray emission probabilities</td>
<td>Limited application</td>
</tr>
<tr>
<td>$^{86}$Y</td>
<td>Cross-section evaluations; β⁺ and X-ray emission probabilities</td>
<td>Important positron emitter for quantification of dosimetry calculations; decay-data evaluation planned in CRP (2012)</td>
</tr>
</tbody>
</table>
### β⁺ emitters (continued)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{95}$Ru</td>
<td>$^3$He and $^4$He beam cross-section measurements and evaluations</td>
<td>Limited application; many gamma rays, together with ~ 14% β⁺ emission</td>
</tr>
<tr>
<td>$^{120}$I</td>
<td>Cross-section evaluations; β⁺ and X-ray emission probabilities</td>
<td>Decay-data evaluation planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{121}$I</td>
<td>Cross-section measurements and evaluations</td>
<td>Borderline – longer-term consideration (easier to produce than $^{120}$I); many gamma rays, together with ~ 11% β⁺ emission</td>
</tr>
<tr>
<td>$^{124}$I</td>
<td>Cross sections - see previous CRP (IAEA Technical Reports Series No. 473)</td>
<td>Important positron emitter for quantification of dosimetry calculations</td>
</tr>
<tr>
<td>$^{152}$Tb</td>
<td>Cross-section measurements and evaluations</td>
<td>Potentially useful as lanthanide-based positron emitter</td>
</tr>
<tr>
<td>Radionuclide</td>
<td>Requirements</td>
<td>Comments</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$^{44}$Ti/$^{44}$Sc</td>
<td>Cross-section measurements and evaluations; evaluation of parent $T_{1/2}$</td>
<td>Long-lived parent ($T_{1/2}$ of 60 y); difficult to produce; evaluation of $^{44}$Ti $T_{1/2}$ planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{52}$Fe/$^{52}$Mn$^m$</td>
<td>Cross-section and decay-data measurements and evaluations</td>
<td>Special application in MRI + PET</td>
</tr>
<tr>
<td>$^{62}$Zn/$^{62}$Cu</td>
<td>Cross-section measurements and evaluations; $\beta^+$ and X-ray emission probabilities</td>
<td>$^{62}$Zn decay-data evaluation planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{68}$Ge/$^{68}$Ga, $^{82}$Sr/$^{82}$Rb</td>
<td>Cross-section measurements and evaluations</td>
<td>Well-established systems, but inadequate databases</td>
</tr>
<tr>
<td>$^{72}$Se/$^{72}$As</td>
<td>Cross-section measurements and evaluations; $\beta^+$ and X-ray emission probabilities</td>
<td>$^{72}$As decay-data evaluation planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{140}$Nd/$^{140}$Pr</td>
<td>Cross-section measurements and evaluations; Auger-electron and other low-energy electron data for $^{140}$Nd microdosimetry</td>
<td>Radiotherapy + PET; parent $^{140}$Nd(EC) to operate as therapeutic radionuclide, while $^{140}$Pr is positron emitter (<em>in-vivo</em> generator)</td>
</tr>
</tbody>
</table>
## Therapeutic $\beta^-$, X-ray and $\gamma$-ray emitters

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{47}$Sc</td>
<td>Cross-section measurements and evaluations</td>
<td>Low-energy $\beta^-$ emitter</td>
</tr>
<tr>
<td>$^{67}$Cu</td>
<td>Cross sections - see previous CRP (IAEA Technical Reports Series No. 473); decay-data measurements and evaluation, particularly g.s. to g.s. transition</td>
<td>Important radionuclide – emission of low-energy $\beta^-$ particles, and preparation of organometallic complexes; decay-data evaluation planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{103}$Pd</td>
<td>Cross sections - see previous CRP (IAEA Technical Reports Series No. 473); decay-data discrepancies – measurements and evaluation; Auger electrons</td>
<td>Decay-data evaluation and Auger-electron studies planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{131}$Cs</td>
<td>Cross-section measurements and evaluations</td>
<td>X-ray emitter</td>
</tr>
<tr>
<td>$^{131}$Ba</td>
<td>Cross-section measurements and evaluations; decay-data evaluation</td>
<td>X-ray emitter</td>
</tr>
<tr>
<td>$^{161}$Tb</td>
<td>$^{160}$Gd(n,$\gamma$)$^{161}$Gd(\beta$^{-}$)$^{161}$Tb; decay-data measurements and evaluation</td>
<td>Low-energy $\beta^-$ emitter</td>
</tr>
</tbody>
</table>
### Therapeutic $\beta^-$, X-ray and $\gamma$-ray emitters (continued)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{166}$Ho</td>
<td>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($2n,\gamma$)$^{166}$Dy($\beta^-$)$^{166}$Ho</td>
<td>High-flux reactor required for double-neutron capture</td>
</tr>
<tr>
<td>$^{169}$Er</td>
<td>Cross-section measurements and evaluations, including spallation beam cross sections; decay-data measurements and evaluation</td>
<td>Low-energy $\beta^-$ emitter</td>
</tr>
<tr>
<td>$^{175}$Yb</td>
<td>Cross-section measurements and evaluations for charged-particle reactions; decay-data measurements and evaluation</td>
<td>Low-energy $\beta^-$ emitter</td>
</tr>
<tr>
<td>$^{191}$Os /$^{191}$Ir$^m$</td>
<td>Cross-section measurements and evaluations</td>
<td>Low-energy $\beta^-$ emitter for radiotherapy + SPECT; potential in-vivo generator</td>
</tr>
<tr>
<td>$^{191}$Pt /$^{191}$Ir$^m$</td>
<td>Cross-section and decay-data measurements and evaluations</td>
<td>X-ray emitter; potential in-vivo generator</td>
</tr>
</tbody>
</table>
## Therapeutic Auger-electron emitters

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{67}$Ga, $^{111}$In</td>
<td>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</td>
<td>$^{67}$Ga and $^{111}$In of increased application in internal radiotherapy; $^{111}$In Auger-electron studies planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{71}$Ge</td>
<td>Cross-section measurements and evaluations; Auger electrons may become an issue</td>
<td>Half-life is rather long at 11.4 d</td>
</tr>
<tr>
<td>$^{77}$Br</td>
<td>Cross-section evaluations; Auger electrons may become an issue</td>
<td></td>
</tr>
<tr>
<td>$^{99}$Tc$^{m}$</td>
<td>Auger-electron ($E_e &lt; 25$ keV) and other low-energy electron ($E_e &lt; 1$ keV) data for microdosimetry; nuclear decay data evaluated in previous CRP (IAEA-STI/PUB/1287); further needs for cross-section data will arise if produced by charged-particle reactions</td>
<td>Regularly used for diagnosis, but also increased application in therapeutics; Auger-electron studies planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{103}$Pd</td>
<td>Cross sections evaluated in previous CRP (IAEA-TECDOC-1211); decay-data measurements and evaluation</td>
<td>Decay-data evaluation and Auger-electron studies planned in CRP (2012)</td>
</tr>
<tr>
<td>Radionuclide</td>
<td>Requirements</td>
<td>Comments</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>$^{123}$I</td>
<td>See IAEA-TECDOC-1211 and IAEA-STI/PUB/1287; Auger electrons</td>
<td>Regularly used for diagnosis, but also increased application in therapeutics; several production reactions and discrepancies to be studied in planned CRP</td>
</tr>
<tr>
<td>$^{140}$Nd</td>
<td>Cross-section evaluations of several reactions; Auger electrons may become an issue</td>
<td>Auger and EC decay; <em>in-vivo</em> generator ($^{140}$Pr) – see previous table (β⁺ emitters: generators)</td>
</tr>
<tr>
<td>$^{178}$Ta</td>
<td>$^{176}$Hf(α,2n)$^{178}$W(EC)$^{178}$Ta; Auger electrons may become an issue</td>
<td>Auger and EC decay; <em>in-vivo</em> generator ($^{178}$W); Auger-electron studies planned in CRP (2012)</td>
</tr>
<tr>
<td>$^{193}$Pt⁺, $^{195}$Pt⁺</td>
<td>Cross-section measurements and evaluations; Auger electrons may become an issue</td>
<td>Large number of Auger electrons emitted</td>
</tr>
<tr>
<td>$^{197}$Hg</td>
<td>Cross-section and decay-data measurements and evaluations; Auger electrons may become an issue</td>
<td></td>
</tr>
</tbody>
</table>
# Therapeutic α emitters

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{149}$Tb</td>
<td>Cross-section measurements and evaluations of spallation and heavy-ion beam reactions</td>
<td>Emission of low-energy alpha particles ($&lt; 4$ MeV) – potentially useful for special applications</td>
</tr>
<tr>
<td>$^{211}$At/$^{211}$Po</td>
<td>Cross sections and decay data evaluated in previous CRPs (IAEA Technical Reports Series No. 473, and “Updated Actinide Decay Data Library (to be published)”)</td>
<td>Well-established therapeutic radionuclide</td>
</tr>
<tr>
<td>$^{225}$Ac/$^{213}$Bi</td>
<td>Lack of cross-section data at higher energies for spallation reaction on $^{232}$Th; nuclear decay chain evaluated in previous CRP (“Updated Actinide Decay Data Library” (to be published))</td>
<td>Potentially important therapeutic radionuclide</td>
</tr>
<tr>
<td>$^{227}$Ac/$^{223}$Ra</td>
<td>Inadequate cross-section data for $^{232}$Th($p,x$) production of $^{227}$Ac – measurements and evaluation; $^{223}$Ra nuclear decay data evaluated in previous CRP (“Updated Actinide Decay Data Library” (to be published))</td>
<td>Impurity in $^{225}$Ac production</td>
</tr>
<tr>
<td>$^{230}$U/$^{226}$Th</td>
<td>Cross-section studies within planned CRP; decay-data evaluations of complete α-decay chain</td>
<td>New decay-data measurements presented at ICRM2011 conference; decay-data evaluation planned for complete decay chain in CRP (2012)</td>
</tr>
</tbody>
</table>
Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data

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IAEA Headquarters, Vienna, Austria
22-26 August 2011

Proton beam therapy:
- non-elastic cross sections of C, N and O at $E_p$ up to 250 MeV;
- activation cross sections of residual nuclei ($^{11}$C, $^{13}$N, $^{15}$O, $^{30}$P and $^{38}$K positron emitters)

Carbon beam therapy – complex fragmentation reactions → difficult to prepare data sets

Fragmentation and production of light particles and residues → require more precise models and validated parameter sets
Proton beam therapy → require more precise Monte-Carlo transport calculations for dose deposition of variations in morphology or in structure arising from bone or implants

Alan Nichols
ICTP, Trieste, Italy, 30 September – 4 October 2013
Nuclear Data Needs

Immediate future:

IAEA-NDS CRP launched in late 2012 is dedicated to cross sections and decay data for medical applications 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 ($\to$ $^{213}$Bi); $^{227}$Ac impurity
- electron and X-ray emitters – $^{131}$Cs (also $^{131}$Ba production)

Decay data evaluations: $^{52}$Fe, $^{61,64,67}$Cu, $^{62,63}$Zn, $^{66}$Ga, $^{72}$As, $^{73}$Se, $^{76}$Br, $^{86}$Y, $^{89}$Zr, $^{94}$Tc$^{m}$, $^{103}$Pd, $^{120}$I, $^{230}$U decay chain $^{44}$Ti half-life, Auger electrons: $^{99}$Tc$^{m}$, $^{103}$Pd, $^{111}$In, $^{178}$Ta

Alan Nichols

ICTP, Trieste, Italy, 30 September – 4 October 2013
Intermediate-term Nuclear Data Needs for **Medical Applications:** Cross Sections and Decay Data

Technical Meeting  
IAEA Headquarters, Vienna, Austria  
22-26 August 2011

**Longer term:**  
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
Intermediate- and longer-term considerations – 5 to 15/20 years?

Further need for future IAEA-NDS CRP(s) dedicated to cross sections and decay data for medical applications based on recommendations:

Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data

A.L. Nichols, S.M. Qaim and R. Capote Noy

22-26 August 2011, IAEA Headquarters, Vienna, Austria
IAEA Report INDC(NDS)-0596, September 2011

Previous tables refer
Where to get the data

- Nuclear Science Division: ie.lbl.gov
- TUNL Nuclear Data Evaluation Project: www.tunl.duke.edu/nucldata
- Nuclear Data Services: www-nds.iaea.org
IAEA-NDS Medical Portal

Repository for and dissemination of nuclear data for medical applications:

IAEA-NDS Medical Portal must be the focal point

http://www-nds.iaea.org/medportal/
\(\alpha, \beta^+, \gamma\) and Auger-electron Decay Data in Nuclear Medicine – Experimental Determination, Status and Deficiencies

assistance in the assembly of this presentation is gratefully acknowledged from:
T. Kibedi, Australian National University, Canberra, Australia;
F.G. Kondev, Argonne National Laboratory, Argonne, IL, USA

along with extensive preliminary discussions at IAEA, Vienna, Austria, with:
R. Capote Noy, Nuclear Data Section, IAEA, Vienna, Austria;
S.M. Qaim, Institut für Neurowissenschaften und Medizin, Nuklerchemie,
Forschungszentrum Jülich GmbH, Jülich, Germany

Workshop on Nuclear Data for Science and Technology: Medical Applications
ICTP, Trieste, Italy, 30 September – 4 October 2013