Summary of identified nuclear reaction data needs for medical applications of radionuclides

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Background: Nuclear Data for Medical Applications

IAEA-NDS relevant past for production cross-section data needs:

- Cross sections − CRP 1995−2000: Charged Particle Cross-Section Database for Medical Radioisotope Production: Diagnostic Radioisotopes and Monitor Reactions, **IAEA-TECDOC-1211**, May 2001
- Cross sections − CRP 2003−2010: Nuclear Data for the Production of Therapeutic Radionuclides, **IAEA Technical Reports Series No. 473**, IAEA, Vienna, Austria, December 2011
- High-Precision Beta-intensity Measurements and Evaluations for Specific PET Radioisotopes (see **IAEA report INDC(NDS)-0535**, 2008)
- Intermediate-term Nuclear Data Needs for Medical Applications: Cross Sections and Decay Data (see IAEA report **INDC(NDS)-0596**, 2011)
- Cross sections − CRP 2012−2017: Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production,
  - ✓ A. Hermanne, *et al*., Reference Cross Sections for Charged-particle Monitor Reactions. *Nuclear Data Sheets* **148** (2018) 338-382.
  - ✓ F.T. Tárkányi, *et al*., Recommended Nuclear Data for Medical Radioisotope Production: Diagnostic Gamma Emitters, *J. Radioanal. Nucl. Chem*. **319** (2019) 487-531, doi.org/10.1007/s10967-018-6142-4.
  - ✓ F.T. Tárkányi, *et al*., Recommended Nuclear Data for Medical Radioisotope Production: Diagnostic Positron Emitters, *J. Radioanal. Nucl. Chem*. **319** (2019) 487-531, doi.org/10.1007/s10967-018-6142-4.
  - ✓ J.W. Engle, *et al*., Recommended Nuclear Data for the Production of Selected Therapeutic Radionuclides, *Nuclear Data Sheets* **155** (2019) 56-74.
- Nuclear Data Needs for Medical Applications (see IAEA report **INDC(NDS)-0776**, 2019)
- Cross sections − DDP 2018−2020: Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production, update of the medical database:
  - ✓ A. Hermanne, *et al*., Upgrade of IAEA recommended data of selected nuclear reactions for production of PET and SPECT isotopes; to be submitted to Nuclear Data Sheets, July 2020

^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{64}Cu, and ^{124}I β^+-emitters and two γ-emitters, ^{81}Rb and ^{123}I, used in SPECT imaging.

ND needs: INDC(NDS)-0776, Vienna, TM 12/2018

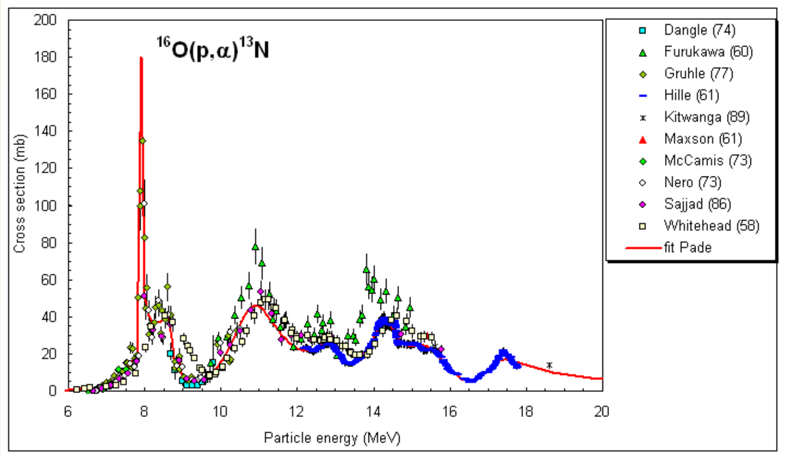
WARNING: Presented needs limited to reaction data

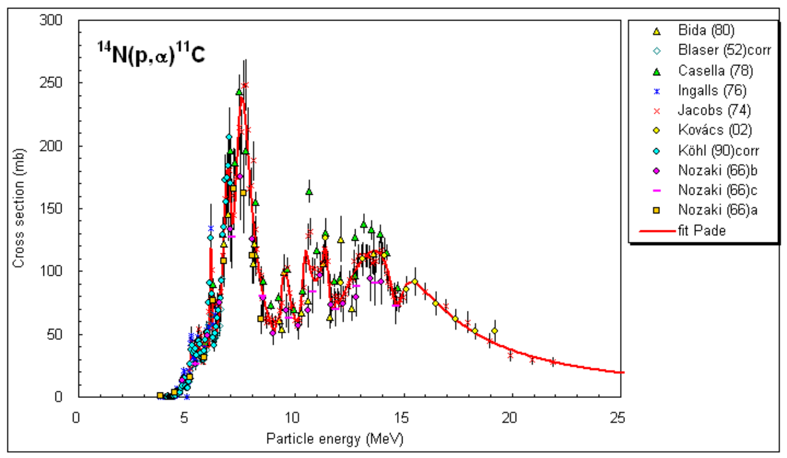
ND needs: INDC(NDS)-0776, TM 12/2018

High Priority / Lower priority

- ✓ **EXTERNAL THERAPY: PROTON BEAMS, CARBON BEAMS, He-4 BEAMS**
- ✓ **Data needed to improve the quantification of the delivered therapeutic dose**

- ✓ **1.- gamma production in proton induced reactions from 20-85 MeV**
  $^{12}C(p,x\gamma)$, $^{14}N(p,x\gamma)$, $^{16}O(p,x\gamma)$ $^{nat}P(p,x\gamma)$, $^{nat}Ca(p,x\gamma)$
- ✓ **2.- Positron-emitter production in proton induced reactions from 20 up to 250 MeV**
  $^{12}C(p,x)^{11}C$, $^{14}N(p,x)^{11}C$, $^{16}O(p,x)^{11}C$, $^{14}N(p,x)^{13}N$, $^{16}O(p,x)^{13}N$, $^{16}O(p,x)^{15}O$
  $^{11}C(p,x)^{10}C$, $^{14}N(p,x)^{12}N$





https://www-nds.iaea.org/medical/positron_emitters.html

ND needs: INDC(NDS)-0776, TM 12/2018

High Priority / Lower priority

- ✓ **CROSS SECTIONS FOR RADIONUCLIDE PRODUCTION in accelerators**

- ✓ **1.- SPECT Radionuclides up to ~100 MeV:**
  - ✓ **Tc-99m production on Mo targets**
  - ✓ **Tb-155 production: ^{155}Gd(p,n)^{155}Tb, ^{156}Gd(p,2n) ^{155}Tb, ^{155}Gd(d,2n)^{155}Tb**
  - ✓ **Os-191 production: ^{190}Os(d,p)^{191}Os**
  - ✓ **Ru-97 production: ^{103}Rh(p,x)^{97}Ru, ^{nat}Mo(α,x) ^{97}Ru**

- ✓ **2.- Therapeutic α-emitters, ^{225}Ac, ^{211}At, ^{212}Pb/^{212}Bi, ^{213}Bi, ^{227,226}Th, ^{149}Tb, ^{230}U**

- **^{225}Ac:** ***^{226}Ra(n,2n)^{225}Ra→^{225}Ac, ^{226}Ra(γ,x)^{225}Ra→^{225}Ac, ^{226}Ra(p,2n)^{225}Ac, ^{226}Ra(p,n)^{226}Ac, ^{226}Ra(n,x)^{229}Th, ^{232}Th(p,x)^{229}Th, ^{232}Th(p,x)^{225}Ra→^{225}Ac.***
- **^{227,226}Th, ^{230}U: ^{230}Pa→^{230}U→^{226}Th.** ***^{232}Th(p,3n)^{230}Pa, ^{232}Th(d,4n)^{230}Pa.*** **A decay chain with multiple potential radionuclides for targeted alpha therapy, especially ^{230}U and $^{226\mathrm{Th}}$; existing discrepant data.**
- **Production of ^{149}Tb, ^{212}Pb/^{212}Bi.**

ND needs: INDC(NDS)-0776, TM 12/2018

High Priority / Lower priority

✓ **CROSS SECTIONS FOR RADIONUCLIDE PRODUCTION in accelerators**

✓ **3.- PET radionuclides up to ~100 MeV:**

- **^{45}Ti. *^{45}Sc(p,n)^{45}Ti, ^{45}Sc(d,2n)^{45}Ti.* Can be produced in extremely high yields from targets of naturally monoisotopic scandium; has a lower positron energy than any other radionuclide apart from ^{18}F.**
- **^{72}Se/^{72}As. *^{nat}Rb(p,x)^{72}Se* at high energy and *^{75}As(p,4n)^{72}Se* (and production of ^{70,71,73,75}Se) up to 200 MeV. ^{72}As is PET-imaging counterpart for β⁻-emitting ^{77}As.**
- **^{76}Br. *^{79}Br(p,4n)^{76}Kr (14.8 h)→^{76}Br.* Theranostic with Auger-electron emitter ^{77}Br.**
- **^{83}Sr. *^{85}Rb(p,3n)^{83}Sr, ^{82}Kr(^{3}He,2n)^{83}Sr*. Theranostic with β⁻ emitter ^{89}Sr.**
- **^{86}Y. *^{87g,87m,88}Y* from *^{87,88}Sr* up to 50 MeV. *^{89}Y(p,4n)^{86}Zr→^{86}Y.* Theranostic with ^{90}Y**
- **^{152}Tb. *^{155}Gd(p,4n)^{152}Tb*. Several potential theranostic applications when used with terbium radionuclides ^{149}Tb, ^{155}Tb, and ^{161}Tb.**

ND needs: INDC(NDS)-0776, TM 12/2018

High Priority / Lower priority

✓ **CROSS SECTIONS FOR RADIONUCLIDE PRODUCTION in accelerators**

✓ **3.- PET radionuclides up to ~100 MeV (lower priority):**

- **^{51}Mn.** $^{54}Fe(p,\alpha)^{51}Mn$, $^{54}Fe(d,\alpha n)^{51}Mn$, $^{50}Cr(d,n)^{51}Mn$, $^{nat}V(^{3}He,x)^{51}Mn$, $^{nat}Fe(p,x)^{51}Mn$. **Short-lived, low-dose alternative to ^{52g}Mn ($T_{1/2}$ = 5.59 d, β^+ = 29.6%), which has several high energy gamma rays.**
- **^{69}Ge.** $^{nat}Ga(p,x)^{69}Ge$, $^{nat}Ga(d,x)^{69}Ge$, $^{69}Ga(p,x)^{69}Ge$, $^{69}Ga(d,2n)^{69}Ge$. **Attractive PET isotope that is theranostic with ^{71}Ge, a pure Auger-electron emitter.**
- **^{34m}Cl:** $^{36}Ar(d,\alpha)^{34m}Cl$, $^{nat}Cl(p,x)^{34m}Cl$, $^{32}S(\alpha,pn)^{34m}Cl$, $^{35}Cl(p,pn)^{34m}Cl$, $^{nat}S(p,n)^{34m}Cl$, $^{nat}S(d,2n)^{34m}Cl$, $^{31}P(\alpha,n)^{34m}Cl$.
- **^{38}K.** $^{38}Ar(p,n)^{38}K$, $^{40}Ar(p,3n)^{38}K$, $^{35}Cl(\alpha,n)^{38}K$.
- **^{43}Sc.** $^{43}Ca(p,n)^{43}Sc$, $^{42}Ca(d,n)^{43}Sc$, $^{40}Ca(\alpha,p)^{43}Sc$, $^{40}Ca(\alpha,n)^{43}Sc$. **Theranostic with β^- emitting ^{47}Sc. Emits fewer high-energy γ rays than ^{44}Sc.**

ND needs: INDC(NDS)-0776, TM 12/2018

CROSS SECTIONS FOR RADIONUCLIDE PRODUCTION in accelerators

- ✓ **3.- Therapeutic radionuclides:**
- ✓ **^{47}Sc. ^{48}Ca(p,2n)^{47}Sc, ^{48}Ca(p,pn)^{47}Ca → ^{47}Sc, ^{48}Ti(p,2p)^{47}Sc, ^{49}Ti(p,x)^{47}Sc, ^{49}Ti(p,3p)^{47}Ca →^{47}Sc, ^{50}Ti(p,x)^{47}Sc, ^{50}Ti(p,x)^{47}Ca→^{47}Sc, ^{nat}V(p,x)^{47}Sc, ^{48}Ca(γ,x)^{47}Ca→^{47}Sc, ^{48}Ca(n,2n)^{47}Ca→^{47}Sc, ^{46}Ca(n,γ)^{47}Ca→^{47}Sc; ^{48}Ca(p,2n)^{47}Sc. ^{48}Ca(d,3n) ^{47}Sc.**
- ✓ **^{77}Br. ^{75}As(α,2n)^{77}Br, ^{77}Se(p,n)^{77}Br, ^{78}Se(p,2n)^{77}Br, ^{79,81}Br(p,xn)^{77}Kr→^{77}Br, ^{nat}Rb(p,x)$^{77/82}$Br. Auger-electron emitter theranostic with positron-emitting ^{76}Br.**

- ✓ **4.- Auger and Coster-Kronig electron emitting nuclei (therapeutic)**

- **^{119}Sb. ^{119}Sn(p,n)^{119}Sb, ^{119}Sn(d,2n)^{119}Sb, ^{120}Sn(p,2n)^{119}Sb, ^{121}Sb(p,3n)^{119}Te→^{119}Sb, ^{121}Sb(d,4n)^{119}Te→^{119}Sb, ^{122}Sn(p,4n)^{119}Sb, ^{117}Sn(α,2n)^{119}Te→^{119}Sb, ^{117}Sn(^{3}He,n)^{119}Te→^{119}Sb.**
- **^{134}Ce/^{134}La. ^{139}La(p,6n)^{134}Ce and reactions to produce main impurities of ^{132,133,135,137,139}Ce up to 200 MeV.**
- **^{165}Er. ^{165}Ho(p,n)^{165}Er, ^{165}Ho(d,2n)^{165}Er, ^{166}Er(p,2n)^{165}Tm→^{165}Er, ^{166}Er(d,3n)^{165}Tm→^{165}Er, ^{nat}Er(p,xn)^{165}Tm→^{165}Er and ^{164}Er(d,n)^{165}Tm→^{165}Er.**

- **^{117m}Sn. *^{116}Cd(α,3n)^{117m}Sn, ^{121}Sb(p,2pxn)^{113,117m,121m,121g}Sn, ^{nat}In(α,pxn)^{117m}Sn, ^{nat}Sb(p,x)^{113,117m,121m,121g}Sn.***