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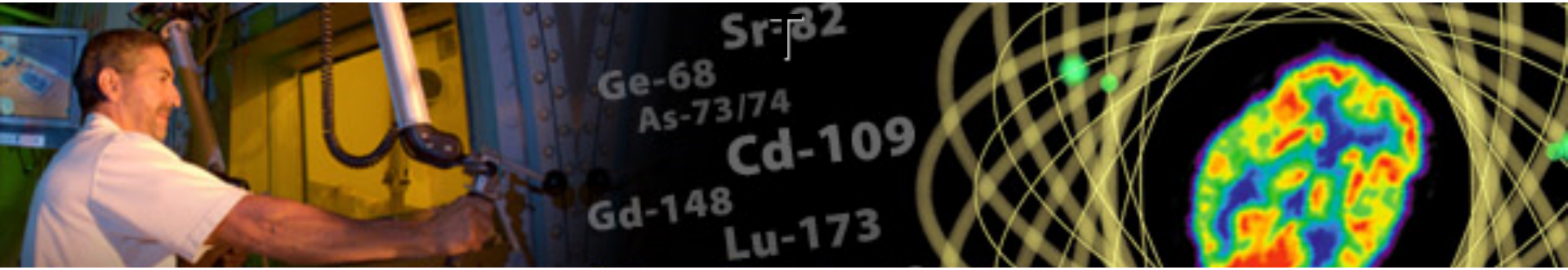
# Nuclear Data for Isotope Production: A Program Manager's Perspective




## Workshop on Applied Nuclear Data Activities (WANDA)
## January 23, 2019

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**Isotope R&D Program Manager, DOE Isotope Program**

**Office of Nuclear Physics, Office of Science, U.S. Department of Energy**

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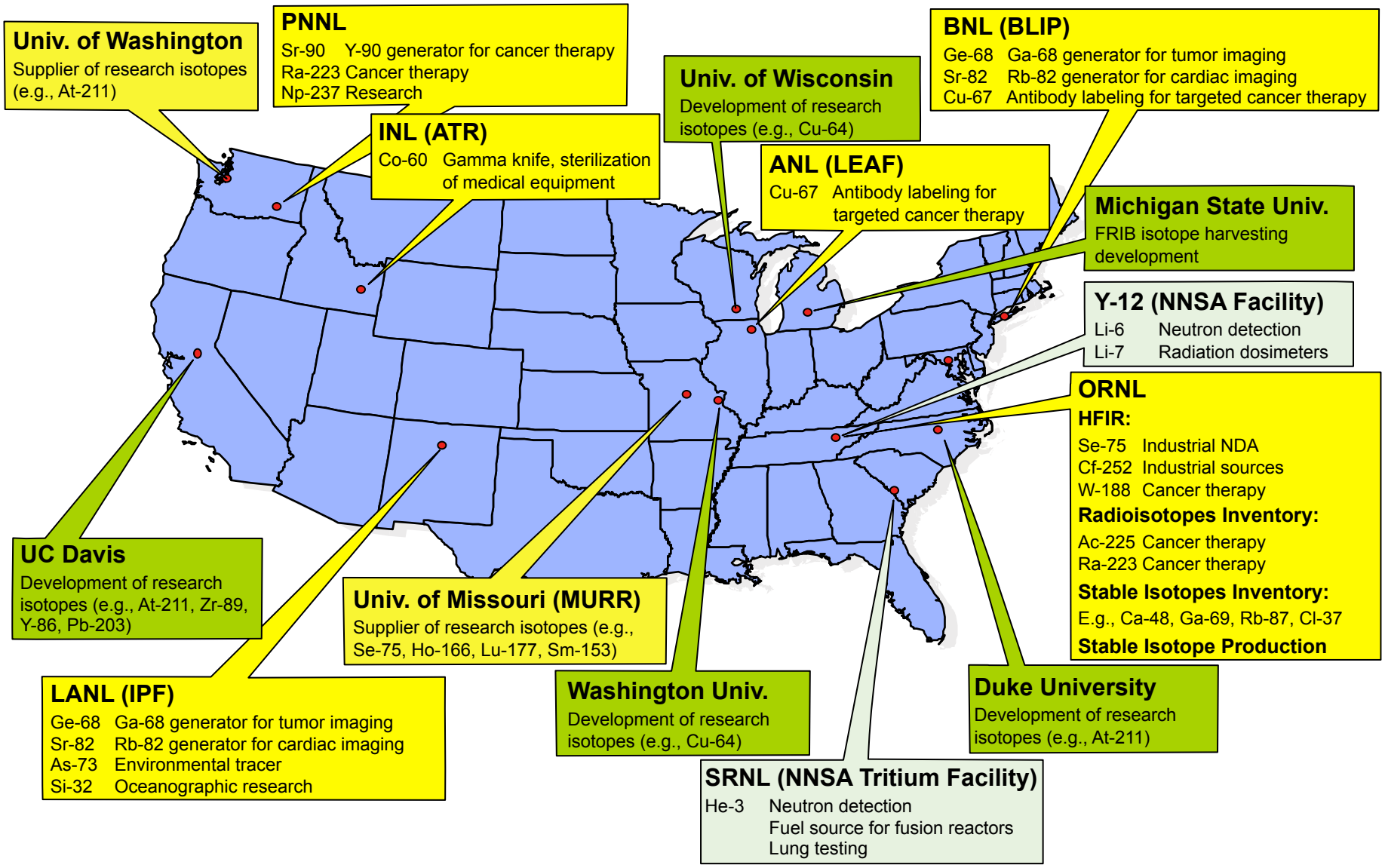
# DOE Isotope Program Production and/or Development Sites



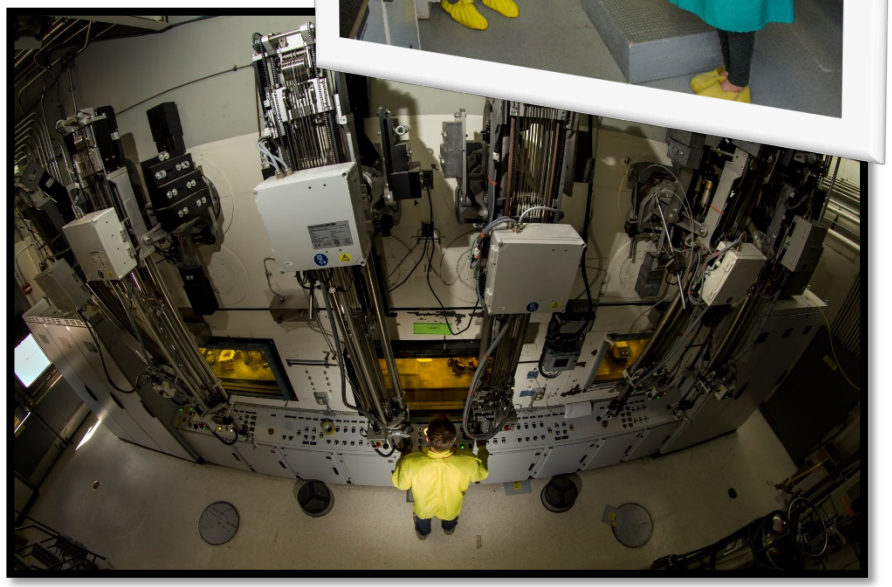
# Stewarded Accelerator Facilities

## Brookhaven National Laboratory Brookhaven Linac Isotope Producer (BLIP)

- The BLIP beam line directs protons up to 160 μA intensity to targets; parasitic operation with nuclear physics programs for more cost effective isotope production.
- Ac-225, Sr-82, Ge-68, Be-7, Cu-67, Y-86, Zn-65, Fe-52, Rb-83


## Los Alamos National Laboratory Isotope Production Facility (IPF)

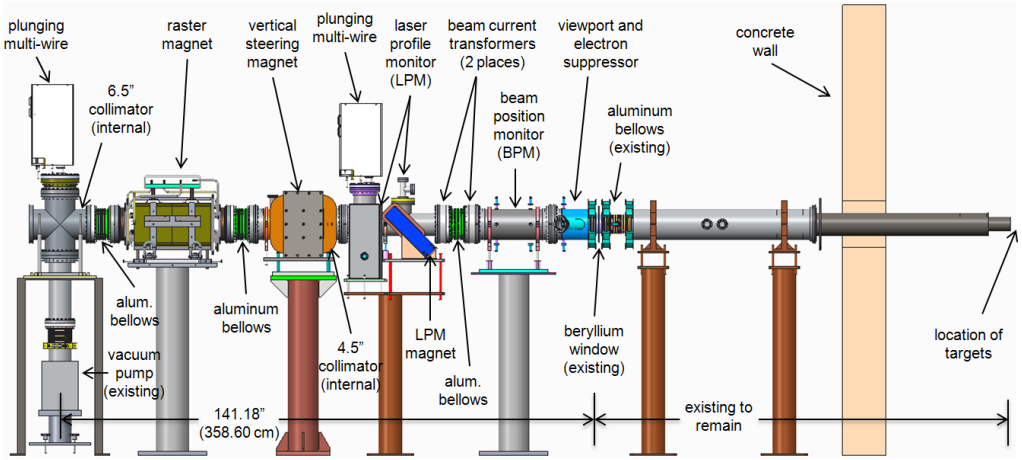
- Diversion of 100 MeV proton beam to target station.
- Irradiates targets while LANSCE operates for NNSA.
- Ac-225, Sr-82, Ge-68, Na-22, As-73, Se-72, Y-88, Si-32, Cd-109

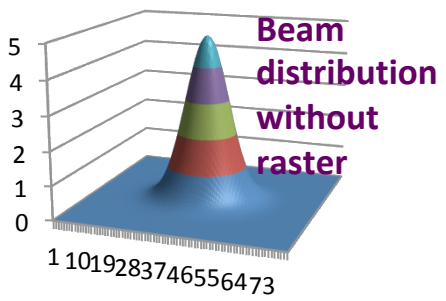


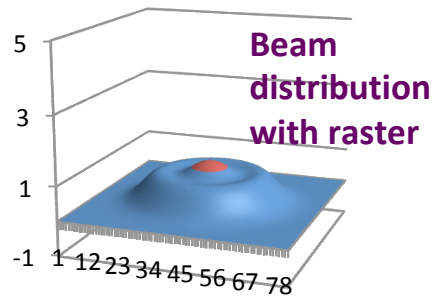
# Major Initiatives to Increase Isotope Production Capabilities

## (BLIP) Beam Raster System

- Added equipment to
  - Raster the proton beam
  - Provide enhanced beam diagnostics
- Enabled increase in beam current on target (greater isotope yields)
  - Maximum current increased from 125 to 140 μA by modification of proton pulses.
  - Actually achieved >160 μA
  - Current had been limited to <100 μA to prevent target failure
- Lowered possibility of target failures



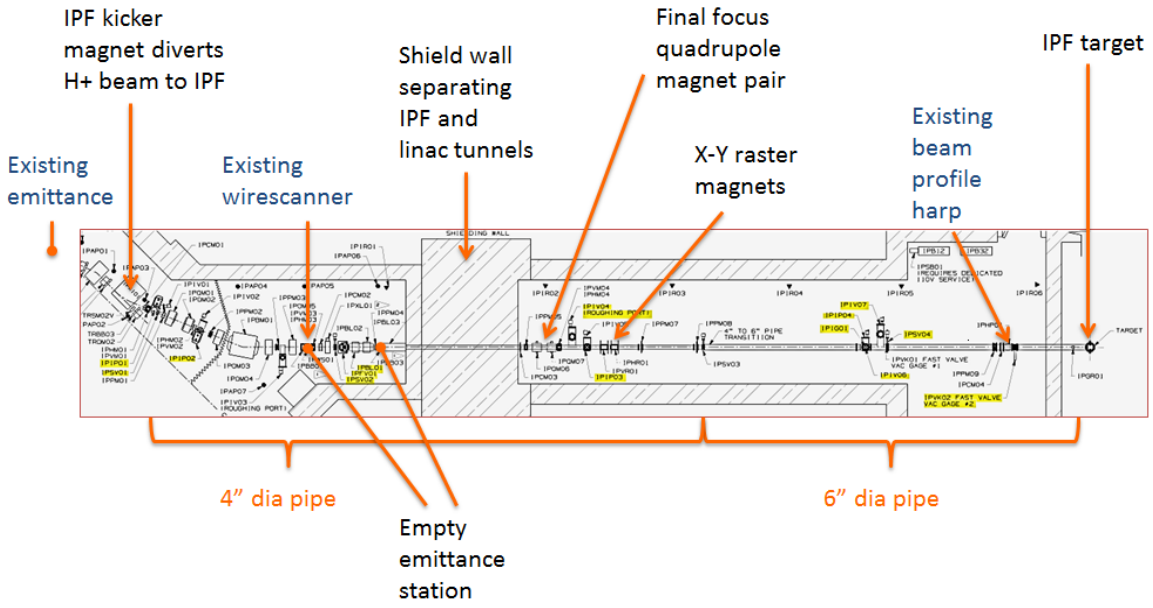



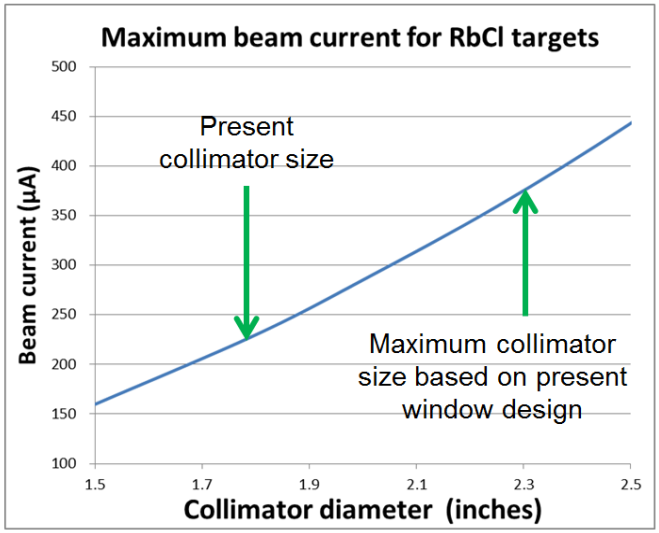

Integral of beam distribution is the same for both plots

# Major Initiatives to Increase Isotope Production Capabilities (cont'd)

## (IPF) Beam Transport Upgrade

- Project completed Summer 2017 (prior to IPF operating cycle)
- Enables increase in beam current from 230 μA to 380 μA
  - 65% increase in production yields
- Improves R&D capabilities and enhances facility reliability
  - Beam energy, current, profile, and emittance measurements



# Isotope Program Nuclear Data Needs or "Meiring's List"- Charged Particles

**Nuclear Reactions for Proton Flux Monitoring:**

Production cross sections are needed as a function of particle energy. Care must be taken in the 80-200 MeV range to address potential secondary neutron related concerns.

| Nuclear reaction | Energy range |
|---|---|
| $^{nat}Nb(p,4n)^{90}Mo$ | Up to 200 MeV |
| $^{nat}Cu(p,xn)^{62,64}Zn$ | Up to 200 MeV |
| $^{nat}Ti(p,x)^{48}V$ | Up to 200 MeV |

**Excitation Functions for Isotope Production:**

Production cross sections are needed as a function of particle energy.

| Isotope | Target | Incident particle | Measurement type | Energy range |
|---|---|---|---|---|
| $^{236}Np$ | $^{235}U$ | d | Excitation functions for production of $^{236m,236g}Np$ | Up to 50 MeV |
| | | d | Excitation functions for production of co-produced impurity: $^{234,235}Np$ | Up to 50 MeV |
| | $^{236}U$ | p | Excitation functions for production of $^{236m,236g}Np$ | Up to 30 MeV |
| | | p | Excitation functions for production of co-produced impurity: $^{234,235,237}Np$ | Up to 30 MeV |
| | $^{236}U$ | d | Excitation functions for production of $^{236m,236g}Np$ | Up to 50 MeV |
| | | d | Excitation functions for production of co-produced impurity: $^{234,235,237,238}Np$ | Up to 50 MeV |
| | $^{238}U$ | p | Excitation functions for production of $^{236m,236g}Np$ | Up to 50 MeV |
| | | p | Excitation functions for production of co-produced impurity: $^{234,235,237,238,239}Np$ | Up to 50 MeV |
| $^{93m}Nb$ | $^{94}Zr$ | p | Excitation function for production of $^{93m}Nb$ | Up to 70 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{91g,92g,93g,94g}Nb$ | Up to 70 MeV |
| $^{202}Pb$ | $^{203}Tl$ | p | Excitation functions for production of $^{202m,202g}Pb$ | Up to 200 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{198,199,200,201,203}Pb$ | Up to 200 MeV |
| | $^{205}Tl$ | p | Excitation functions for production of $^{202m,202g}Pb$ | Up to 200 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{198,199,200,201,203,204,205}Pb$ | Up to 200 MeV |
| $^{205}Pb$ | $^{206}Pb$ | p | Excitation functions for production of $^{205}Bi$, $^{205}Pb$ | Up to 200 MeV |
| | $^{206}Pb$ | p | Excitation functions for production of co-produced impurities: $^{198,199,200,201,202,203,204,205,206,207}Bi$ | Up to 200 MeV |
| | $^{204}Pb$ | p | Excitation functions for production of co-produced impurities: $^{198,199,200,201,202,203,204}Bi$ | Up to 200 MeV |
| | $^{207}Pb$ | p | Excitation functions for production of $^{205}Bi$ and co-produced impurities: $^{198,199,200,201,202,203,204,206,207}Bi$ | Up to 200 MeV |
| | $^{208}Pb$ | p | Excitation functions for production of $^{205}Bi$ and co-produced impurities: $^{198,199,200,201,202,203,204,206,207,208}Bi$ | Up to 200 MeV |

| Isotope | Target | Incident particle | Measurement type | Energy range |
|---|---|---|---|---|
| $^{134}Ce$ | $^{nat}La$ | p | Excitation function for production of $^{134}Ce$ | Up to 200 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{132,133,133,137,139}Ce$ | Up to 200 MeV |
| $^{72}Se$ | $^{75}As$ | p | Excitation function for production of $^{72}Se$ | Up to 100 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{70,71,73,75}Se$ | Up to 100 MeV |
| $^{47}Sc$ | $^{50}Ti$ | p | Excitation function for production of $^{47}Sc$ | Up to 50 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{43,44,46,48,49}Sc$ | Up to 50 MeV |
| $^{67}Cu$ | $^{70}Zn$ | p | Excitation function for production of $^{67}Cu$ | Up to 50 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{61,62,64,66}Cu$ | Up to 50 MeV |
| $^{86}Sr$ | $^{86}Y$ | p | Excitation function for production of $^{86}Y$ | Up to 50 MeV |
| | | p | Excitation functions for co-produced impurities: $^{87g,87m,88}Y$ from $^{87,88}Sr$ | Up to 50 MeV |
| $^{119}Te$ | $^{nat}Sb$ | p | Excitation functions for production of $^{119m,119g}Te$ | Up to 100 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{116,117,118,121m,121g,123m}Te$ | Up to 100 MeV |
| | $^{121}Sb$ | p | Excitation functions for production of $^{119m,119g}Te$ | Up to 100 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{116,117,118,121m,121g,123m}Te$ | Up to 100 MeV |
| $^{117m}Sn$ | $^{nat}Sb$ | p | Excitation function for production of $^{117m}Sn$ | Up to 100 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{113,119m,121m,121g}Sn$ | Up to 100 MeV |
| | $^{121}Sb$ | p | Excitation function for production of $^{117m}Sn$ | Up to 100 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{113,119m}Sn$ | Up to 100 MeV |
| $^{135}La$ | $^{nat}Ba$ | p | Excitation function for production of $^{135}La$ | Up to 100 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{131,132,133,137}La$ | Up to 100 MeV |

| Isotope | Target | Incident particle | Measurement type | Energy range |
|---|---|---|---|---|
| | $^{135,136}Ba$ | p | Excitation function for production of $^{135}La$ | Up to 50 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{131,132,133,134}La$ | Up to 50 MeV |
| $^{186}Re$ | $^{189}Os$ | p | Excitation function for production of $^{186}Re$ | Up to 50 MeV |
| | | p | Excitation functions for production of co-produced impurities: $^{181,182m,182g,183,184,184g,188m,188g,189}Re$ as well as contributing pre-cursers such as $^{181,182,183}Os$ and $^{181,182,183}Ir$ | Up to 50 MeV |

# Isotope Program Nuclear Data Needs or "Meiring's List"- Charged Particles

Other nuclear data needs for intermediate energy production of medical isotopes are listed below. Excitation functions are needed up to 100 MeV (preferably up to 200 MeV) for production of the primary isotope and for all co-produced isotopic impurities. In each case the main production nuclear reaction is indicated but it should be noted that in some cases more than one nuclear reaction contribute to the production of a particular isotope or isotopic impurity. The needs listed below are considered important but of slightly lower priority.

| **Non-standard $\beta^+$ emitters** | **SPECT radionuclides and generator parents** | **Therapeutic radionuclides** |
|---|---|---|
| $^{55}Mn(p,4n)^{52}Fe$ | $^{124}Xe(p,pn)^{123}Xe$ | $^{68}Zn(p,2p)^{67}Cu$ |
| $^{59}Co(p,3n)^{57}Ni$ | $^{124}Xe(p,2p)^{123}I$ | $^{107}Ag(p,\alpha n)^{103}Pd$ |
| $^{68}Zn(p,\alpha n)^{64}Cu$ | $^{45}Sc(p,2n)^{44}Ti$ | $^{232}Th(p,x)^{225}Ac$ |
| $^{71}Ga(p,4n)^{68}Ge$ | $^{69}Ga(p,2n)^{68}Ge$ | |
| $^{75}As(p,3n)^{73}Se$ | $^{nat}Br(p,x)^{72}Se$ | |
| $^{85}Rb(p,3n)^{83}Sr$ | | |
| $^{88}Sr(p,3n)^{86}Y$ | | |
| $^{125}Te(p,2n)^{124}Te$ | | |

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# Isotope Program Nuclear Data Needs or "Meiring's List"- Photons

**Excitation Functions for Isotope Production:**
Production cross sections are needed as a function of photon energy.

| Nuclear reaction | Photon energy range |
|---|---|
| $^{48}Ti(\gamma,p)^{47}Sc$ | Up to 50 MeV |
| $^{48}Ti(\gamma,pn)^{46}Sc$ | Up to 50 MeV |
| $^{48}Ca(\gamma,n)^{47}Ca$ | Up to 50 MeV |
| $^{48}Ca(\gamma,p)^{47}K$ | Up to 50 MeV |
| $^{68}Zn(\gamma,p)^{67}Cu$ | Up to 50 MeV |
| $^{68}Zn(\gamma,pn)^{66}Cu$ | Up to 50 MeV |
| $^{68}Zn(\gamma,pn)^{66}Cu$ | Up to 50 MeV |
| $^{77}Se(\gamma,p)^{76}As$ | Up to 50 MeV |
| $^{78}Se(\gamma,p)^{77}As$ | Up to 50 MeV |
| $^{78}Se(\gamma,pn)^{76}As$ | Up to 50 MeV |
| $^{187}Os(\gamma,p)^{186}Re$ | Up to 50 MeV |
| $^{189}Os(\gamma,p)^{188}Re$ | Up to 50 MeV |
| $^{190}Os(\gamma,p)^{189}Re$ | Up to 50 MeV |
| $^{196}Pt(\gamma,p)^{195}Ir$ | Up to 50 MeV |
| $^{196}Pt(\gamma,n)^{195m}Pt$ | Up to 50 MeV |
| $^{197}Au(\gamma,pn)^{195m}Pt$ | Up to 50 MeV |
| $^{197}Au(\gamma,n)^{196}Au$ | Up to 50 MeV |
| $^{162}Dy(\gamma,p)^{161}Tb$ | Up to 50 MeV |
| $^{162}Dy(\gamma,pn)^{160}Tb$ | Up to 50 MeV |
| $^{226}Ra(\gamma,n)^{225}Ra$ | Up to 50 MeV |
| $^{226}Ra(\gamma,2n)^{224}Ra$ | Up to 50 MeV |

**Activation of Converter Materials:**
Production cross sections are needed as a function of photon energy for all activation products, with the highest priority on the major gamma dose drivers (both long-lived and short-lived).

| Converter materials | Photon energy range |
|---|---|
| Tungsten | Up to 50 MeV |
| Tantalum | Up to 50 MeV |
| Gold | Up to 50 MeV |
| Copper | Up to 50 MeV |
| Stainless steel | Up to 50 MeV |
| Aluminum | Up to 50 MeV |
| Magnesium | Up to 50 MeV |
| Lead | Up to 50 MeV |
| Rhenium | Up to 50 MeV |
| Platinum | Up to 50 MeV |

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# Isotope Program Nuclear Data Needs or "Meiring's List"- Neutrons

**Nuclear Reactions for Fast Neutron Flux Characterization:**
Production cross sections are needed as a function of neutron energy.
Note: Some data exist for some reactions on these targets. Notwithstanding, confirmation measurements are still needed.

| Nuclear reaction | Energy range |
|---|---|
| $^{209}Bi(n,3n)^{207}Bi$ | Up to 200 MeV |
| $^{209}Bi(n,4n)^{206}Bi$ | Up to 200 MeV |
| $^{209}Bi(n,5n)^{205}Bi$ | Up to 200 MeV |
| $^{209}Bi(n,6n)^{204}Bi$ | Up to 200 MeV |
| $^{nat}Lu(n,xn)^{173}Lu$ | Up to 200 MeV |
| $^{nat}Lu(n,xn)^{172}Lu$ | Up to 200 MeV |
| $^{nat}Lu(n,xn)^{171}Lu$ | Up to 200 MeV |
| $^{nat}Lu(n,xn)^{170}Lu$ | Up to 200 MeV |
| $^{nat}Lu(n,xn)^{169}Lu$ | Up to 200 MeV |
| $^{169}Tm(n,3n)^{167}Tm$ | Up to 200 MeV |
| $^{169}Tm(n,4n)^{166}Tm$ | Up to 200 MeV |
| $^{169}Tm(n,5n)^{165}Tm$ | Up to 200 MeV |

**Fast Neutron Induced Reactions:**
Isotope Production Via Threshold Reactions.
Production cross sections are needed as a function of neutron energy.

| Nuclear reaction | Energy range |
|---|---|
| $^{232}Th(n,x)^{225}Ac$ | Up to 200 MeV |
| $^{232}Th(n,x)^{227}Ac$ | Up to 200 MeV |
| $^{36}S(n,x)^{32}Si$ | Up to 200 MeV |
| $^{nat}K(n,x)^{32}Si$ | Up to 200 MeV |
| $^{37}Cl(n,x)^{32}Si$ | Up to 200 MeV |
| $^{35}Cl(n,x)^{32}Si$ | Up to 200 MeV |
| $^{68}Zn(n,x)^{67}Cu$ | Up to 200 MeV |
| $^{70}Zn(n,\alpha)^{67}Ni$ | Up to 200 MeV |
| $^{50}Ti(n,x)^{47}Sc$ | Up to 200 MeV |
| $^{50}Ti(n,\alpha)^{47}Ca$ | Up to 200 MeV |
| $^{226}Ra(n,2n)^{225}Ra$ | Up to 200 MeV |

# Isotope Program Nuclear Data Needs or "Meiring's List"- Neutrons

Other nuclear data needs for fast neutron production of medical isotopes are listed below. These measurements are also considered important but of slightly lower priority. Excitation functions are typically needed up to 200 MeV.

| | | | | |
|---|---|---|---|---|
| $^{32}S(n,p)^{32}P$ | $^{67}Zn(n,p)^{67}Cu$ | $^{149}Sm(n,p)^{149}Pm$ | $^{161}Dy(n,p)^{161}Tb$ | $^{175}Lu(n,p)^{175}Yb$ |
| $^{47}Ti(n,p)^{47}Sc$ | $^{89}Y(n,p)^{89}Sr$ | $^{153}Eu(n,p)^{153}Sm$ | $^{166}Er(n,p)^{166m,166g}Ho$ | $^{177}Hf(n,p)^{177m,177g}Lu$ |
| $^{64}Zn(n,p)^{64}Cu$ | $^{105}Pd(n,p)^{105}Rh$ | $^{159}Tb(n,p)^{159}Gd$ | $^{169}Tm(n,p)^{169}Er$ | |

Low-Energy Neutron Reactions: Isotope Production Via Reactors
Energy-resolved cross sections as well as effective cross sections for both thermal neutrons and epi-thermal neutrons are needed for production at U.S. based reactors (e.g. HFIR and ATR).

| Nuclear reaction | Nuclear reaction | Nuclear reaction |
|---|---|---|
| **Data for production of $^{229}Th$ and other isotopes** | **Data for SHE target isotopes production** | **Data for $^{252}Cf$ production** |
| $^{227}Ra(n,\gamma)^{228}Ra$ - confirmation measurement needed | $^{248}Cm(n,\gamma)$ low energy resonances<br>$^{249}Bk(n,\gamma)$ | $^{245}Cm(n,\gamma)$ |
| $^{228}Ra(n,\gamma)^{229}Ra$ | $^{250}Cf(n,\gamma)$ and $^{250}Cf(n,f)$<br>$^{251}Cf(n,\gamma)$ and $^{251}Cf(n,f)$ – first resonance | $^{247}Cm(n,\gamma)$ |
| $^{228}Ac(n,\gamma)^{229}Ac$ | | $^{248}Cm(n,\gamma)$ |
| $^{227}Th(n,\gamma)^{228}Th$ - confirmation measurement needed | | $^{249}Bk(n,\gamma)$ |
| $^{228}Th(n,\gamma)^{229}Th$ - confirmation measurement needed | | $^{250}Cf(n,g)$ and $^{250}Cf(n,f)$ |
| $^{229}Th(n,\gamma)^{230}Th$ - confirmation measurement needed | | $^{251}Cf(n,g)$ and $^{251}Cf(n,f)$ |
| $^{229}Th(n,fission)$ - confirmation measurement needed | | $^{252}Cf(n,X)$ - resonance near 1eV in particular |
| $^{227}Th(n,fission)$ - confirmation measurement needed | | |
| $^{187}W(n,\gamma)^{188}W$ - reported value not reliable | | |
| $^{133}Ba(n,\gamma)^{134}Ba$ - confirmation measurement needed | | |
| $^{107}Ag(n,\gamma)^{108}Ag \rightarrow {}^{108}Cd(n,\gamma)^{109}Cd$ - confirmation measurements needed | | |

# Isotope Program Nuclear Data Initiative

- Representatives from BNL, LANL, and LBNL did a down select and prioritization on “Meiring’s List” for a comprehensive nuclear data generation plan specific to isotope production.
- Multi-year effort involving all three sites
  - Will establish a robust nuclear data capability across the 0 – 200 MeV proton energy range, that can continue to be utilized into the future
  - Will establish identical counting capabilities at each site
  - All sites will evaluate each irradiated sample ensuring triplicate data sets

# Infrastructure Upgrades???

- ***Targetry:***
  - Fabrication
    - Thin films vs Full thickness
    - Trade capabilities (i.e. pellet pressing, foil rolling, machining, welding, etc.)
  - Design
    - Thermal modeling based on power deposition

- ***Instrumentation/Data Acquisition:***
  - Multiple measurements vs. single data points
  - Uniformity of counting statistics

- ***What am I missing? What would help you?***

# Summary

- DOE IP has and will continue to have significant nuclear data needs requiring investment from it's R&D portfolio.

- Our investments will have a direct impact on the products and services that we are able to provide.

- If you have target material needs (i.e. stable or radioisotopes) please contact either your federal program manager, the NIDC for a quote, or me for further discussion. We are implementing a strategy to better meet the needs of the nuclear data community.


Thank You!