Validation of Radioactivity Calculation Code System

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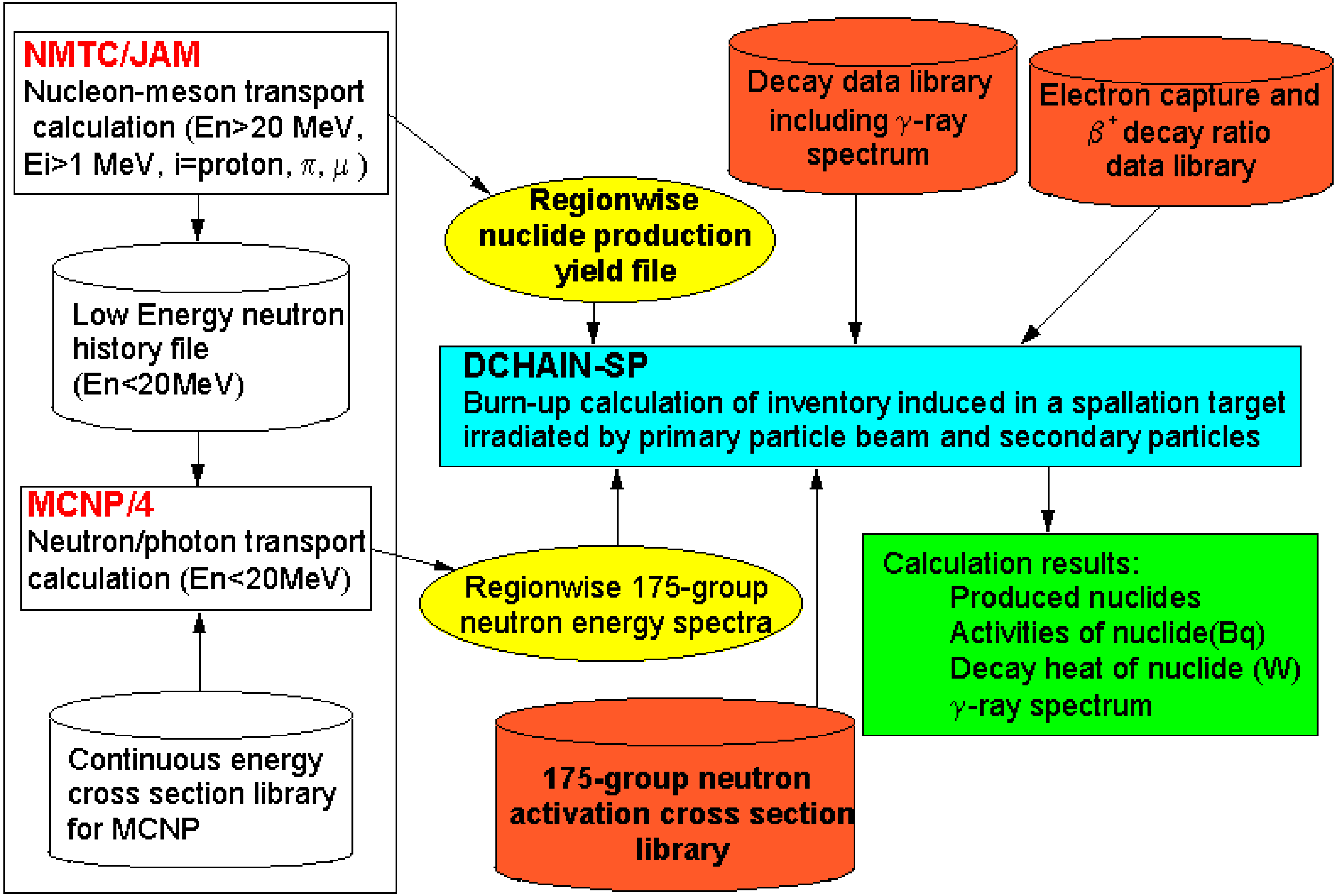
Schematic diagram of DCHAIN-SP code system



Validation Process

1. Activation cross section library

   (for neutrons below 20 MeV)

   - Revision of FENDL/A-2.0
   - Benchmarking by Experiments with 14-MeV neutron

2. Nuclide production yield

   (for neutrons above 20 MeV, proton, pion, muon,…)

   - Implementing GEM model in NMTC/JAM
   - Adopting evaluated cross section data of He-4, N-14, O-16
   - Comparison with experimental data

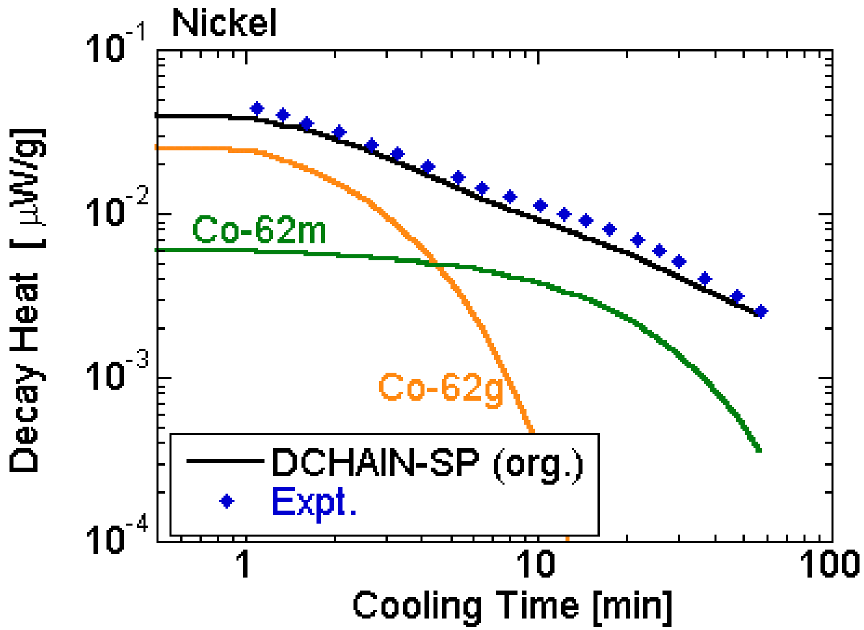
3. Whole code system
   - Benchmarking by AGS activation experiment

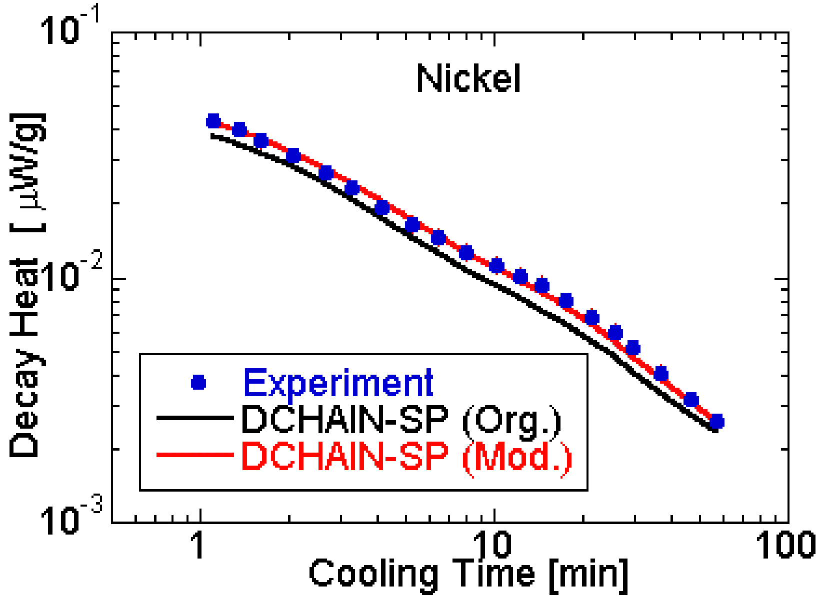
Revision of Cross Section Library FENDL/A-2.0

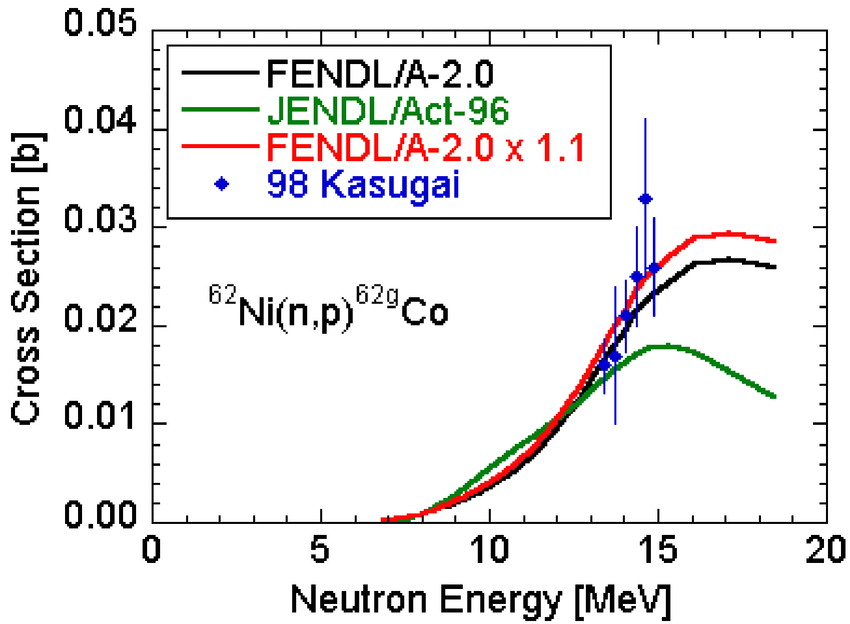
- Experiments by Fusion Neutronics Source
  - Decay heat of 32 fusion reactor materials
  - Activation cross section of Hg
  - Activity, decay heat of Hg

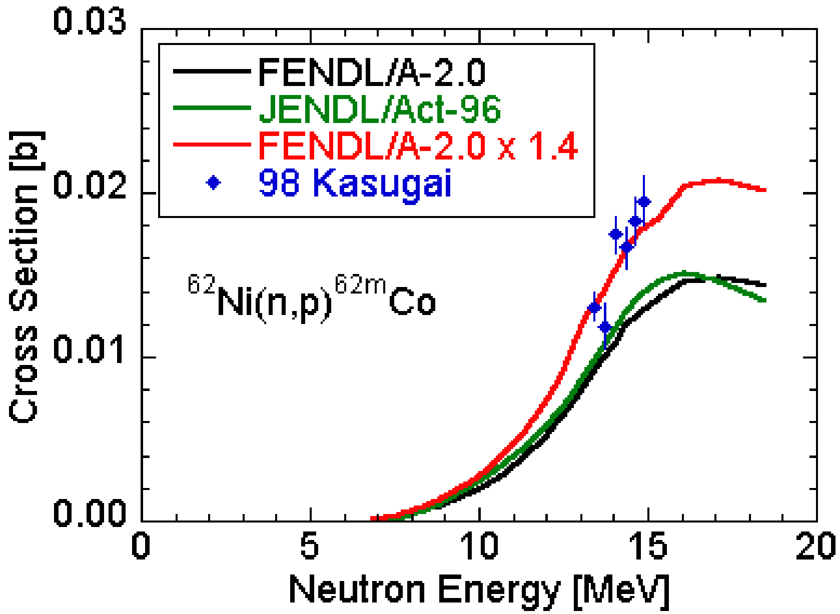
- Tritium production cross section
  - Existing experimental data, systematics

Revision of Cross Sections (Ni)

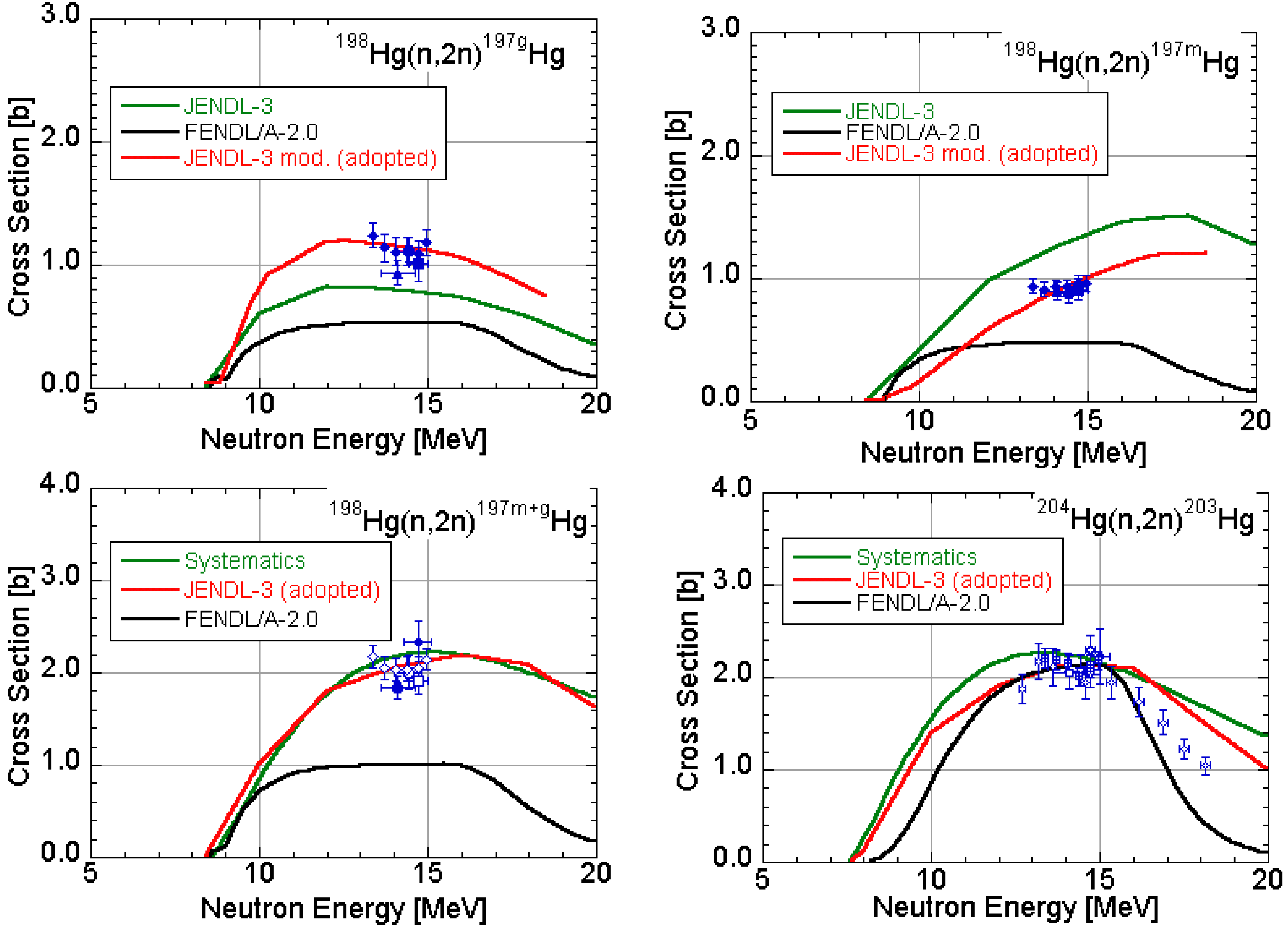




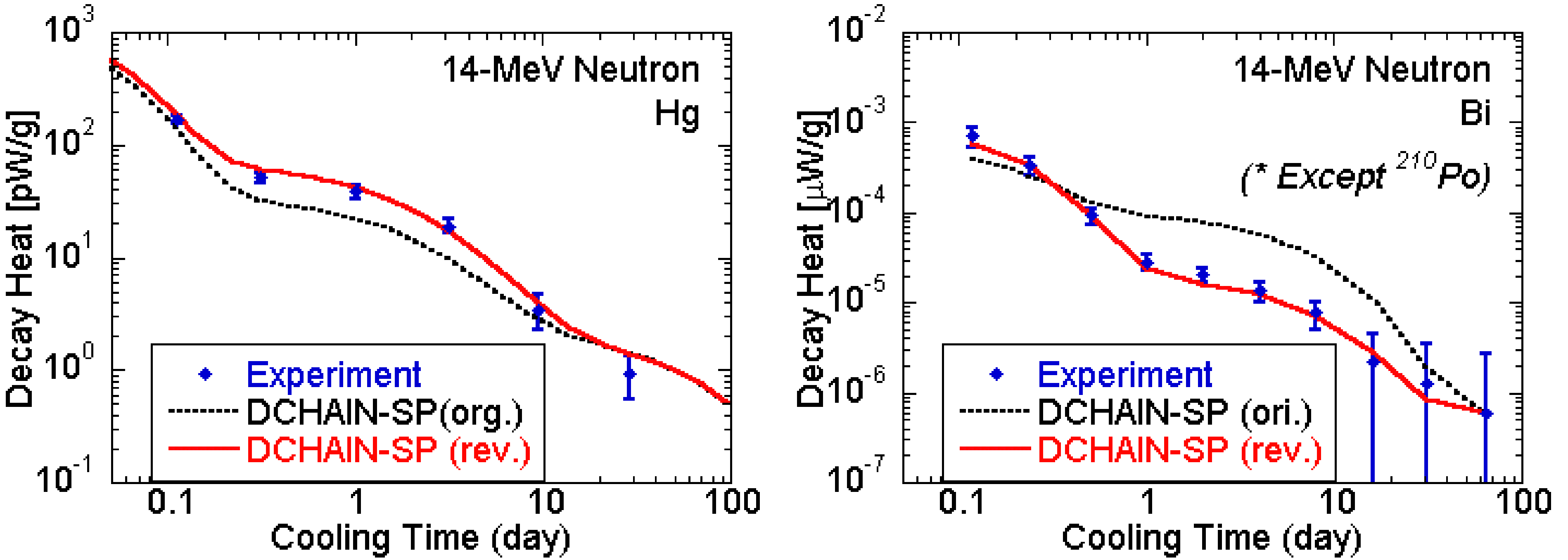




Revision of Cross Sections (Hg)



Improvements after Revision (Hg,Bi)



Lists of Revised Cross Section of FENDL/A-2.0 (1/2)

Revised Reaction	Data Source & Factor for Revision
$^{23}Na(n,2n)^{22}Na$	JENDL/Dosimetry-99
$^{23}Na(n,p)^{23}Ne$	JENDL/Act-96
$^{32}S(n,t)^{30}P$	JENDL/Act-96
$^{40}Ca(n,t)^{38}K$	FENDL/A-2.0 x 1/278.54
$^{50}Ti(n,p)^{50g}Sc$, ^{50m}Sc	JENDL/Act-96 x 1.1
$^{55}Mn(n,a)^{52}V$	FENDL/A-2.0 x 0.9
$^{55}Mn(n,p)^{55}Cr$	JENDL/Act-96
$^{58}Ni(n,p)^{58g}Co$, ^{58m}Co	JENDL/Act-96, low energy tail eliminated
$^{62}Ni(n,p)^{62g}Co$	FENDL/A-2.0 x 1.1
$^{62}Ni(n,p)^{62m}Co$	FENDL/A-2.0 x 1.4
$^{63}Cu(n,a)^{60g}Co$, ^{60m}Co	FENDL/A-2.0 x 1.2
$^{88}Sr(n,2n)^{87m}Sr$	FENDL/A-2.0 x 1.1
$^{88}Sr(n,p)^{88}Rb$	JENDL/Act-96 x 1.3
$^{89}Y(n,a)^{86m}Rb$	FENDL/A-2.0 x 2.0
$^{92}Mo(n,2n)^{91g}Mo$, ^{91m}Mo	JENDL/Act-96
$^{112}Sn(n,2n)^{111}Sn$	JENDL/Act-96 x 1.15
$^{118}Sn(n,p)^{118g}In$, $^{118m1}In$, $^{118m2}In$	FENDL/A-2.0 x 1.6
$^{120}Sn(n,p)^{120g}In$, $^{120m1}In$, $^{120m2}In$	FENDL/A-2.0 x 1.5
$^{185}Re(n,2n)^{184g}Re$, ^{184m}Re	FENDL/A-2.0 x 0.8
$^{181}Ta(n,2n)^{180g}Ta$	JENDL/Act-96
$^{184}W(n,p)^{184}Ta$	JENDL/Act-96
$^{186}W(n,2n)^{185g}W$, ^{185m}W	m/g ratio modified
$^{186}W(n,p)^{186}Ta$	FENDL/A-2.0 x 0.8

Revised Reaction	Data Source & Factor for Revision
$^{196}Hg(n,2n)^{195g}Hg$	JENDL-3.3 x 1.4
$^{196}Hg(n,2n)^{195m}Hg$	JENDL-3.3
$^{198}Hg(n,2n)^{197g}Hg$, ^{197m}Hg	JENDL-3.3, m/g ratio modified
$^{198}Hg(n,p)^{198g}Au$	FENDL/A-2.0 x 1.6
$^{199}Hg(n,2n)^{198}Hg$	JENDL-3.3
$^{199}Hg(n,n')^{199m}Hg$	FENDL/A-2.0 x 0.6
$^{199}Hg(n,p)^{199}Au$	FENDL/A-2.0 x 1.6
$^{200}Hg(n,2n)^{199g}Hg$, ^{199m}Hg	JENDL-3.3
$^{200}Hg(n,p)^{200m}Au$	FENDL/A-2.0 x 5.0
$^{201}Hg(n,2n)^{200}Hg$	JENDL-3.3
$^{201}Hg(n,p)^{201}Au$	FENDL/A-2.0 x 2.0
$^{202}Hg(n,2n)^{201}Hg$	JENDL-3.3
$^{202}Hg(n,p)^{202}Au$	JENDL-3.3
$^{204}Hg(n,2n)^{203}Hg$	JENDL-3.3
$^{204}Hg(n,p)^{204}Au$	JENDL-3.3
$^{204}Pb(n,2n)^{203g}Pb$, ^{203m}Pb	JENDL-3.2, m/g ratio from FENDL/A-2.0
$^{208}Pb(n,p)^{208}Tl$	FENDL/A-2.0 x 1.5
$^{209}Bi(n,p)^{209}Pb$	FENDL/A-2.0 x 2.0
$^{209}Bi(n,g)^{210g}Bi$, ^{210m}Bi	JENDL/Act-96

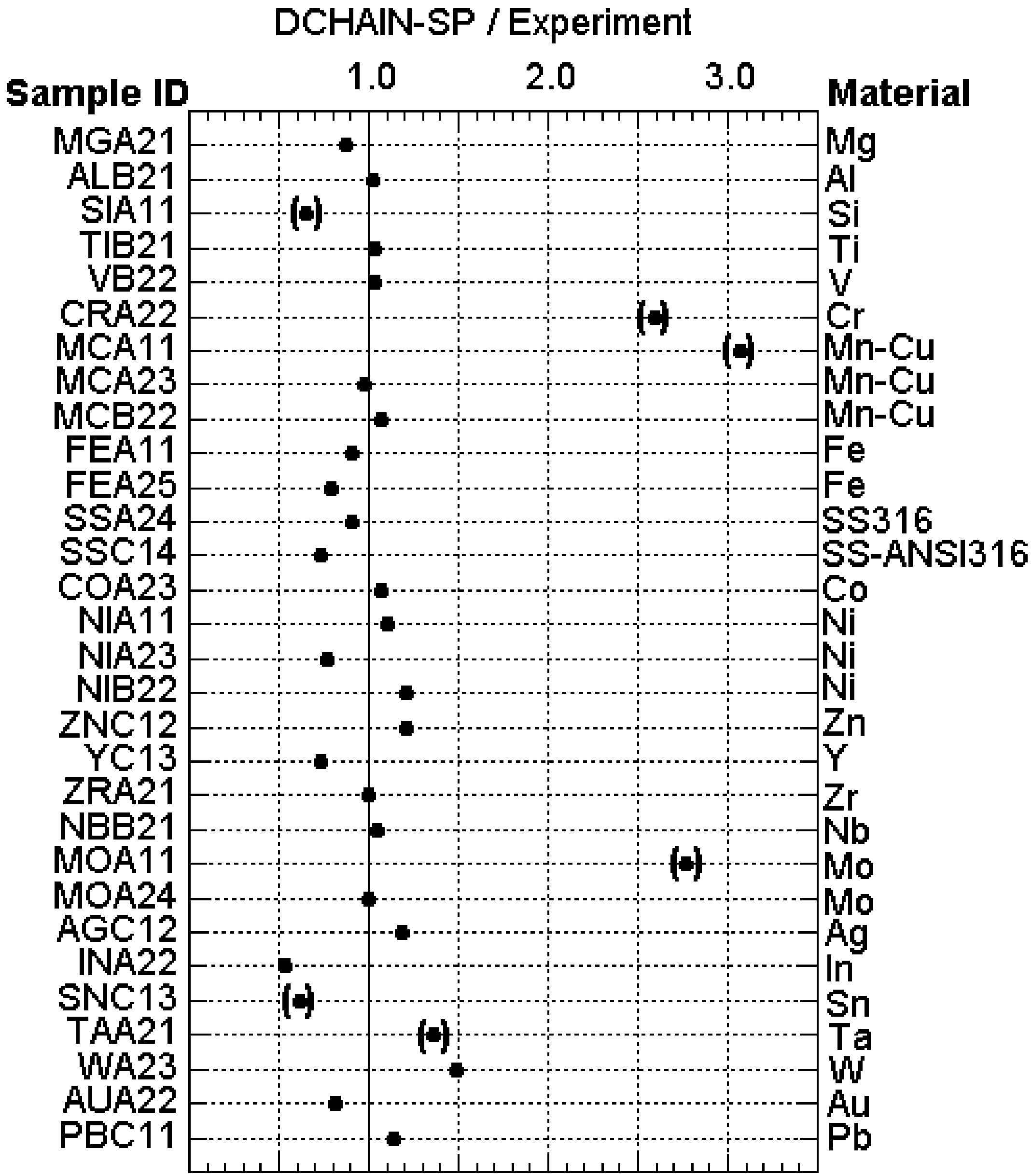
Lists of Revised Cross Section of FENDL/A-2.0 (2/2)

Revised Reaction	Data Source & Factor for revision
$^{10}B(n,t)^{8}Be$	FENDL/A-2.0 x 1.5
$^{16}O(n,t)^{14}N$	FENDL/A-2.0 x 0.02
$^{17}O(n,t)^{15}N$	FENDL/A-2.0 x 10
$^{18}O(n,t)^{16}N$	FENDL/A-2.0 x 100
$^{19}F(n,n't)^{16}O$	FENDL/A-2.0 x 0.1
$^{46}Ti(n,t)^{44m}Sc$, ^{44g}Sc	FENDL/A-2.0 x 0.2
$^{51}V(n,t)^{49}Ti$	FENDL/A-2.0 x 10
$^{53}Cr(n,t)^{51}V$	FENDL/A-2.0 x 0.1
$^{54}Cr(n,t)^{52}V$	FENDL/A-2.0 x 0.1
$^{54}Fe(n,t)^{52m}Mn$	FENDL/A-2.0 x 0.01
$^{54}Fe(n,t)^{52g}Mn$	FENDL/A-2.0 x 0.1
$^{57}Fe(n,t)55Mn$	FENDL/A-2.0 x 5
$^{58}Fe(n,t)^{56}Mn$	FENDL/A-2.0 x 5
$^{65}Cu(n,t)^{63}Ni$	FENDL/A-2.0 x 10
$^{83}Kr(n,t)^{81}Br$	FENDL/A-2.0 x 0.1
$^{92}Mo(n,t)^{90m}Nb$, ^{90g}Nb	FENDL/A-2.0 x 0.01
$^{151}Eu(n,t)^{149}Sm$	FENDL/A-2.0 x 0.1
$^{152}Eu(n,t)^{150}Sm$	FENDL/A-2.0 x 0.1
$^{153}Eu(n,t)^{151}Sm$	FENDL/A-2.0 x 0.1
$^{154}Eu(n,t)^{152}Sm$	FENDL/A-2.0 x 0.1
$^{197}Au(n,t)^{195}Pt$	FENDL/A-2.0 x 0.2
$^{239}Pu(n,t)^{237}Np$	FENDL/A-2.0 x 200

Calculation Test on γ-ray Energy Release

- Total energy release of secondary γ-ray
- DCHAIN-SP can predict most of experimental data within several tens of percent.

** Large discrepancies indicated in parenthesis are not due to the DCHAIN-SP calculations.*



Implementing GEM model in NMTC/JAM

- GEM model is implemented in NMTC/JAM to obtain accurate prediction of the cross section of light fragments such as beryllium produced from proton-induced reactions.

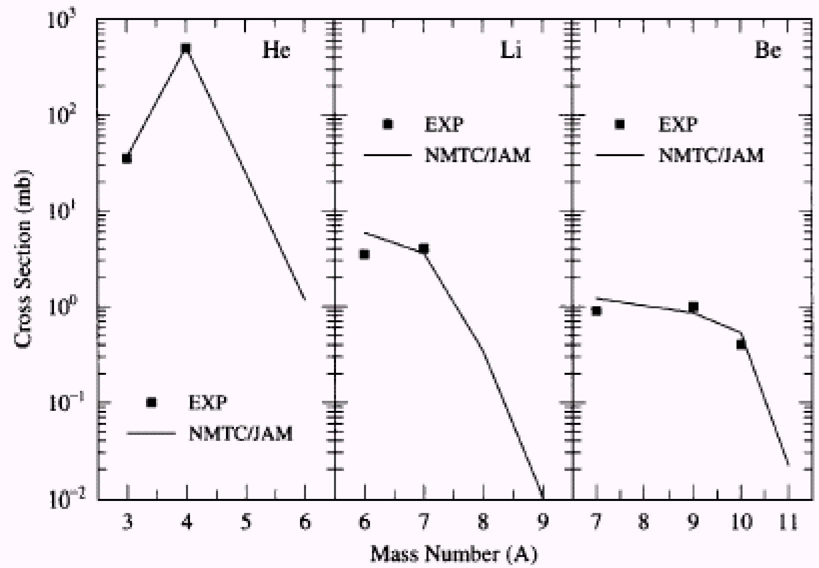


Figure 15. The isotope production cross sections of He, Li and Be from the Ag(p,x) reaction at 480 MeV. The experimental data are taken from Ref. [42]. The results of JAM with GEM are shown by the solid lines.

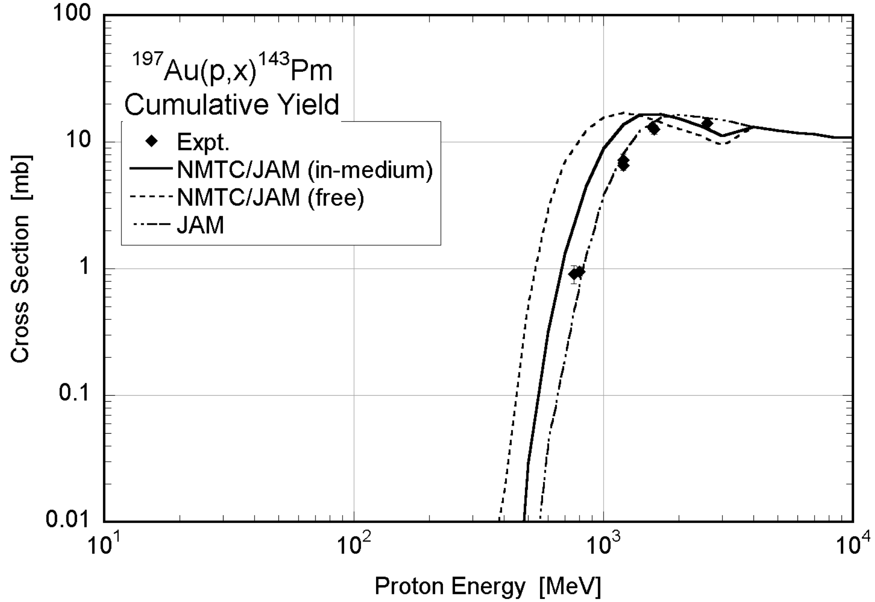
Adopting Evaluated Cross Section Data of He-4, N-14, O-16

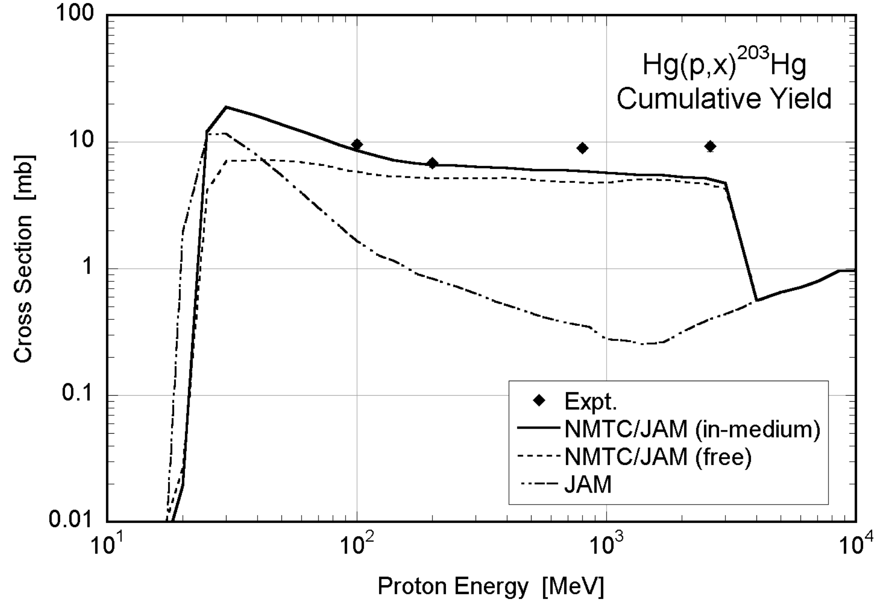
- NMTC/JAM adopted a function to calculate the production rates from helium-4, nitrogen-14 and oxygen-16 using cross section data sets made from experimental data automatically.

$^{4}He(n,x)^{3}H$	$^{14}N(n,x)^{3}H$	$^{14}N(n,x)^{7}Be$	$^{14}N(n,x)^{11}Be$	$^{14}N(n,x)^{10}C$	$^{14}N(n,x)^{11}C$
$^{14}N(n,x)^{14}C$	$^{14}N(n,x)^{13}N$	$^{16}O(n,x)^{3}H$	$^{16}O(n,x)^{7}Be$	$^{16}O(n,x)^{11}Be$	$^{16}O(n,x)^{10}C$
$^{16}O(n,x)^{11}C$	$^{16}O(n,x)^{14}C$	$^{16}O(n,x)^{15}C$	$^{16}O(n,x)^{13}N$	$^{16}O(n,x)^{16}N$	$^{16}O(n,x)^{14}O$
$^{16}O(n,x)^{15}O$	$^{4}He(p,x)^{3}H$	$^{14}N(p,x)^{7}Be$	$^{14}N(p,x)^{11}Be$	$^{14}N(p,x)^{10}C$	$^{14}N(p,x)^{11}C$
$^{14}N(p,x)^{13}N$	$^{14}N(p,x)^{14}O$	$^{16}O(p,x)^{3}H$	$^{16}O(p,x)^{7}Be$	$^{16}O(p,x)^{11}Be$	$^{16}O(p,x)^{10}C$
$^{16}O(p,x)^{11}C$	$^{16}O(p,x)^{14}C$	$^{16}O(p,x)^{13}N$	$^{16}O(p,x)^{14}O$	$^{16}O(p,x)^{15}O$	

Comparison with experimental data & NMTC/JAM

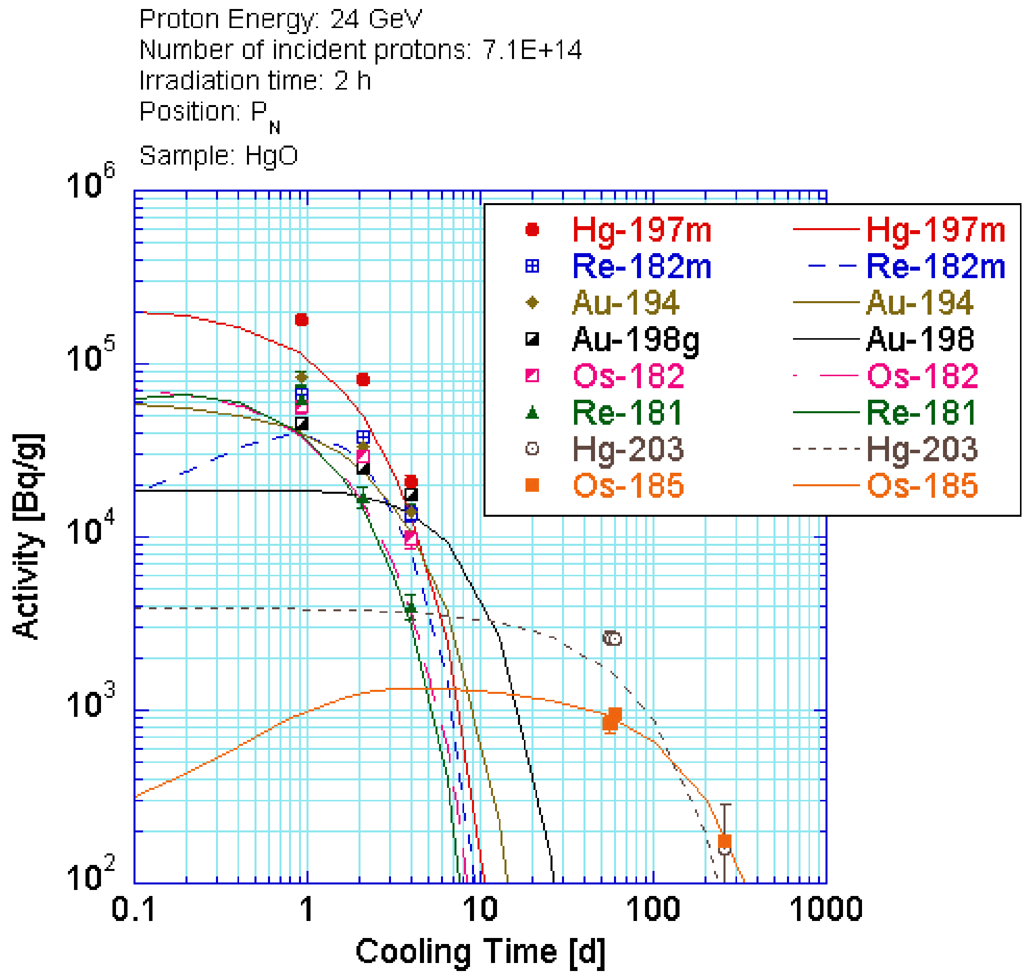
- Proton-induced nuclide production yield.
- Target: C, N, O, Al, Ca, Fe, Cu, Nb, Ba, Au, Hg, Pb, Bi, U
- Proton energy: 10MeV ~ 10 GeV
- 685 reactions
- Experimental data were mainly cited from EXFOR.





Benchmarking by AGS activation experiment

- An activation experiment on carbon, oxygen, boron-10, boron-11, aluminum, copper, iron, niobium, lead, bismuth and mercury using 3 and 24 GeV proton at AGS/BNL was carried out.



Summary

- DCHAIN-SP Code system can predict radioactivity with adequate accuracy.