Lawrence Berkeley National Laboratory
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Final results for $^{182,183,184,186}W(n,\gamma)$

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Brookhaven National Laboratory
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EGAF: Improving the capture-γ spectrum

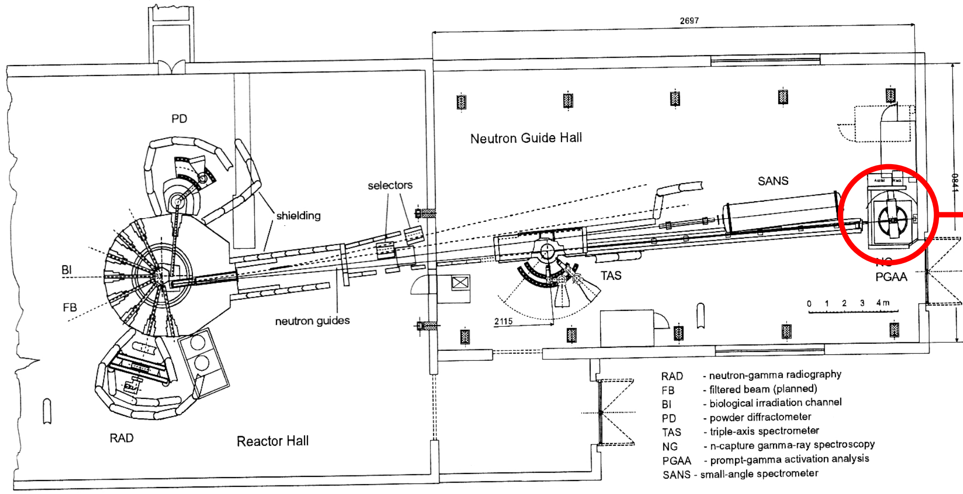
▪ Objective of the project

Collaborative effort to improve the present libraries of capture γ-ray data for a wide range of isotopes for neutron energies in the thermal (22.5 meV) through to the high-energy (20 MeV) regimes

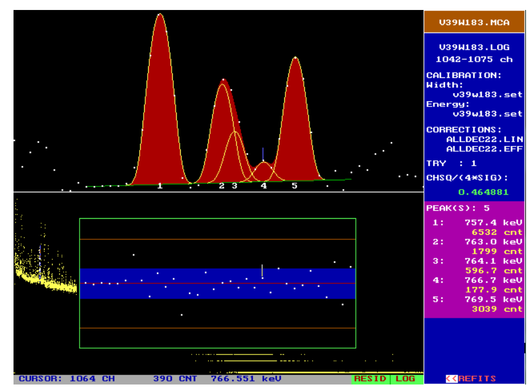
▪ Method: Thermal-neutron energies

- Systematic use and development of the **Evaluated Gamma-ray Activation File (EGAF)**
- Database of thermal-capture γ-ray cross sections from measurements performed at the Budapest Research Reactor (+ Munich Reactor in the future…)
- Compare experimental data to statistical-model expectations using DICEBOX to model thermal-capture γ cascade
- Improve upon known γ-ray decay data and nuclear structure information in the **Evaluated Nuclear Structure Data File (ENSDF)**
- Communicate results through the **Reference Input Parameter Library (RIPL)** in addition to the **Evaluated Nuclear Data File (ENDF)** neutron-data library
- Ultimately: part of a complete library to be disseminated through BNL

EGAF data measured @ Budapest Reactor

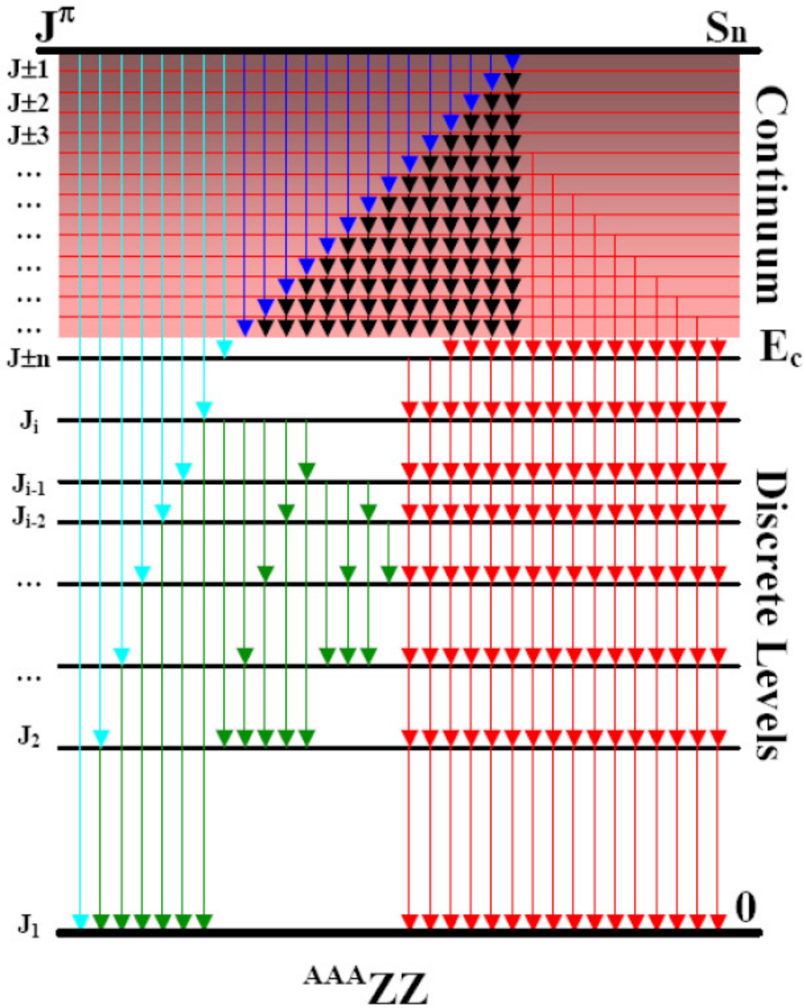


- 10 MW Budapest reactor
- Thermal flux ~ 10^6 cm^{-2}s^{-1}
  Cold flux ~ 10^8 cm^{-2}s^{-1}
- PGAA (Prompt Gamma Activation Analysis) facility ~ 35 m from reactor wall (low background)
- Compton-suppressed HPGe detector (closed-end coaxial) located 23.5 cm from target
- HYPERMET: analysis tool for capture-γ spectra
- ^{184}W(n,γ)



DICEBOX: (n,γ) γ-ray cascade simulations

DICEBOX Monte Carlo Code



DICEBOX generates (n,γ) level scheme simulations (nuclear realizations) based on statistical model level densities $\rho(E_i, J^{\pi}_i)$ and γ-ray transition probabilities Γ_{if} where

a) All levels and γ-rays below E_{crit} are taken from experiment.

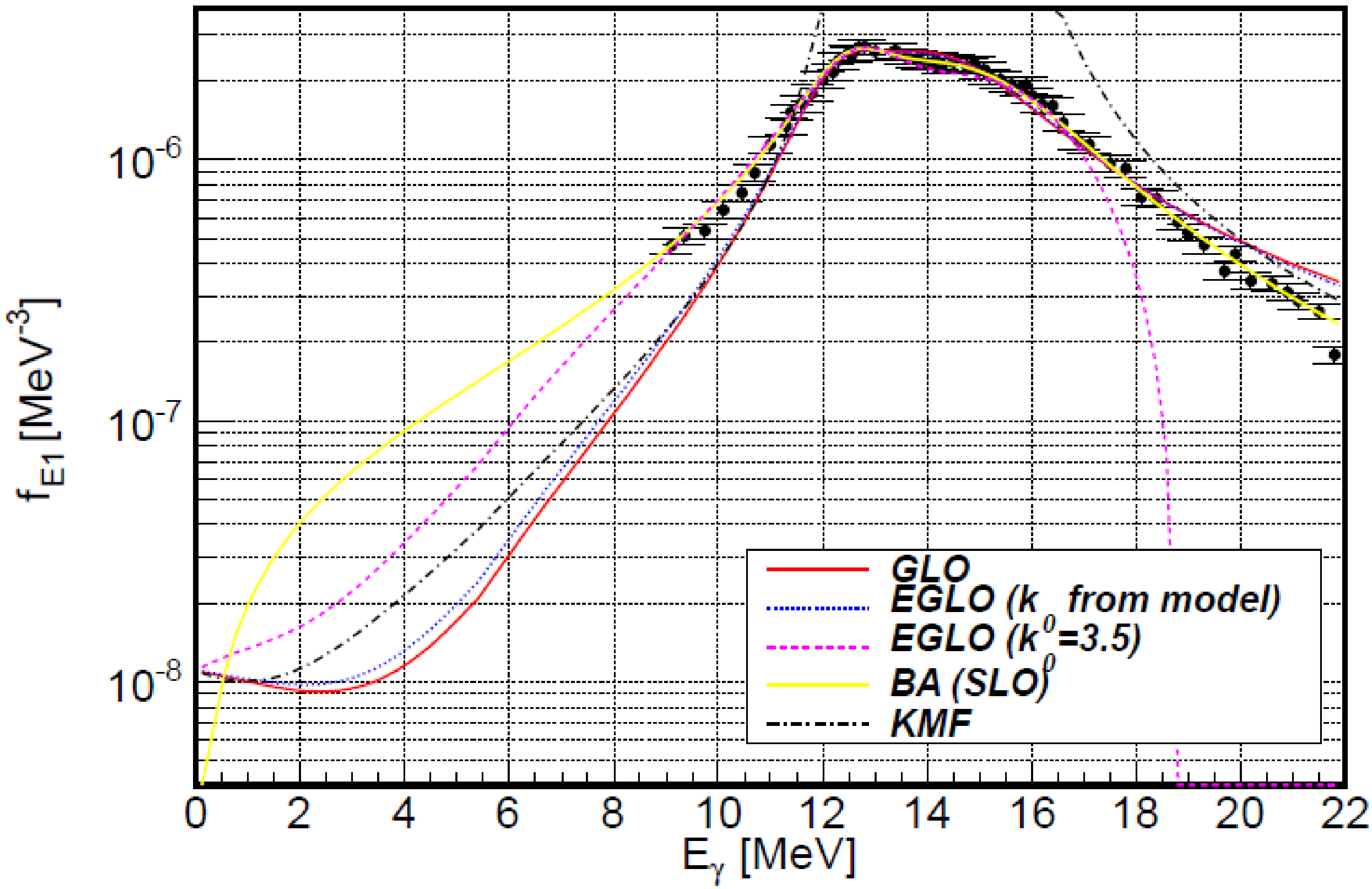
b) All levels and γ-rays above E_{crit} are generated randomly from level density and PSF models

c) Primary γ-ray cross sections are taken from experiment when known.

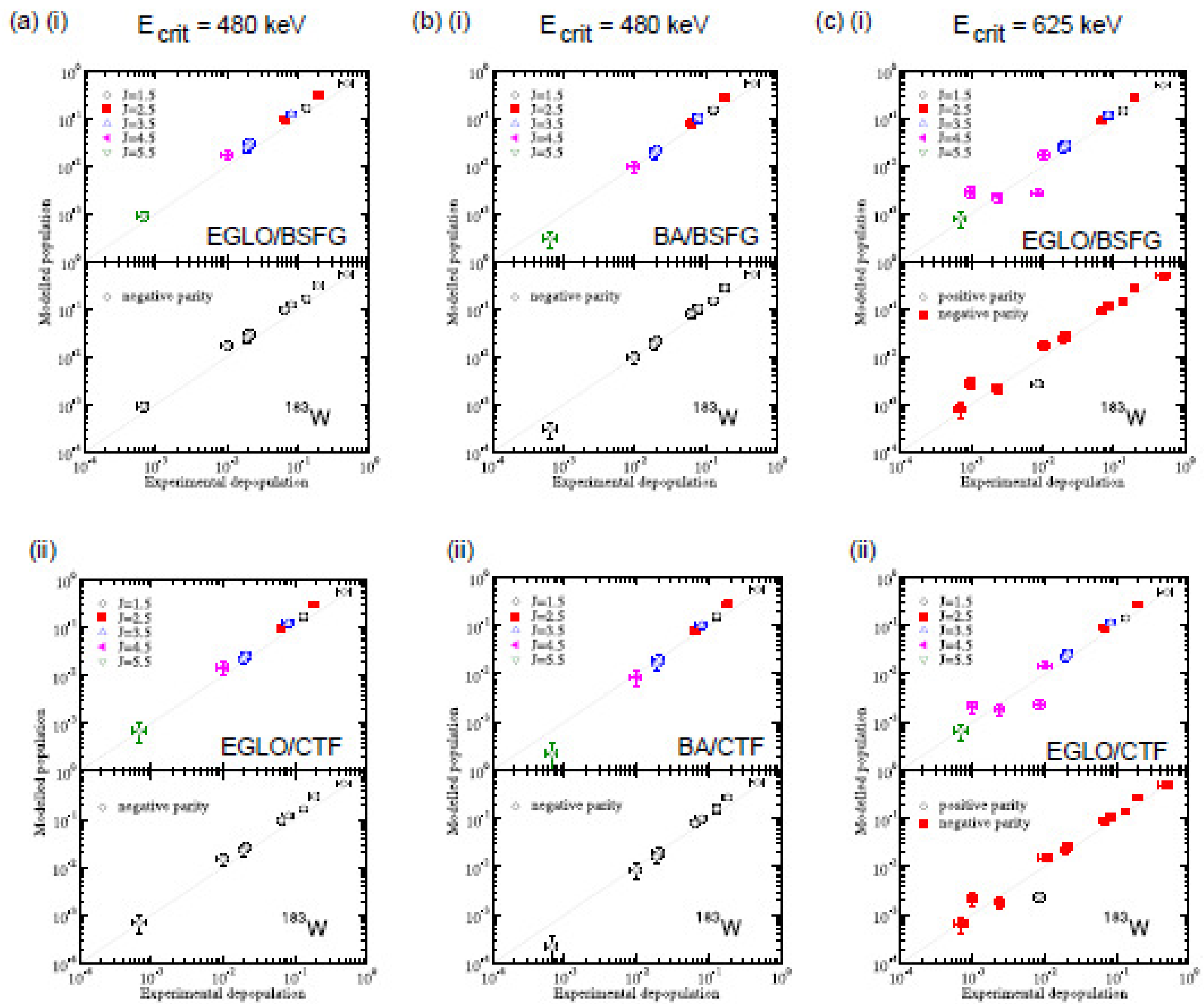
Typically 30,000 capture state γ-ray decay cascades are randomly generated for each nuclear realization.

50 separate realizations are usually averaged to get the statistical variation in the simulated level feedings.

Determining the PSF



Analysis of ^{182}W(n,γ)



The issue with γ-ray self attenuation

- For dense materials (e.g. W) ⇒ self-attenuation may be very big
- Standardize measured peak areas with known σ_γ
- Find common normalization over wide range of energies

75 keV	150 keV	300 keV	1000 keV	6000 keV
← Strong	Significant		Negligable	→

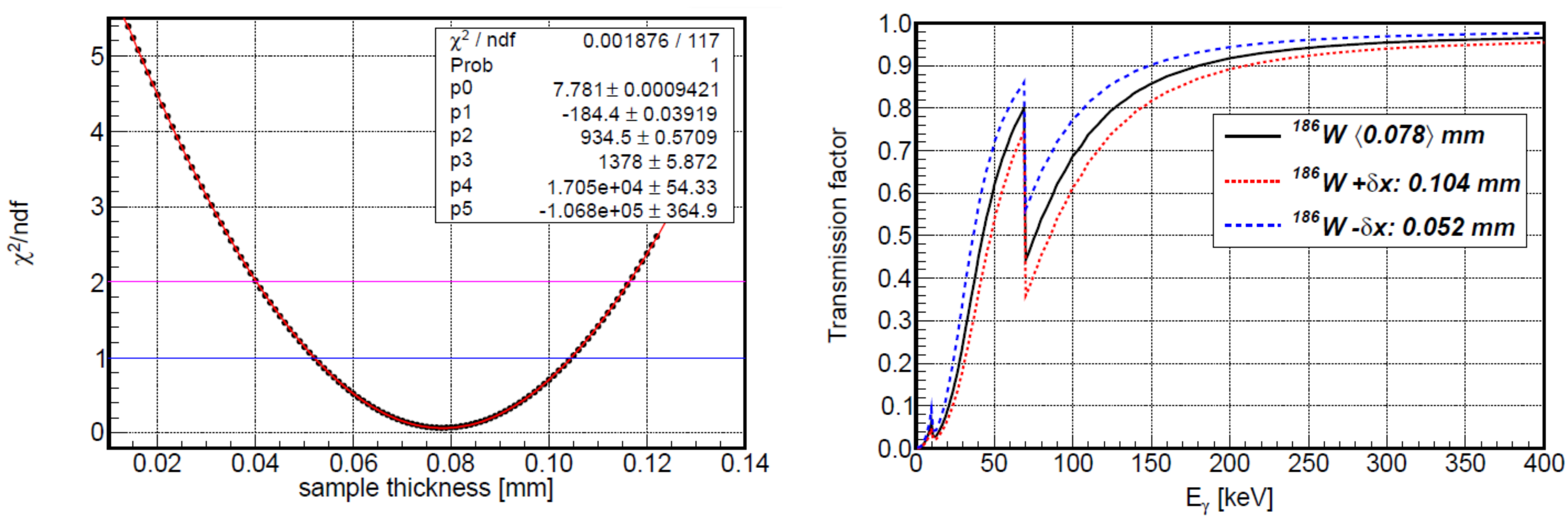
e.g. ^{186}W

0.078 mm

E_γ	σ_γ	N
77.2	0.231(16)	8.85E-06(66)
145.7	1.360(24)	9.24E-06(45)
273.0	0.3836(66)	9.33E-06(94)
1082.0	0.0874(47)	8.92E-06(54)
5261.7	0.642(18)	8.85E-06(29)

Folding self-attenuation into analysis

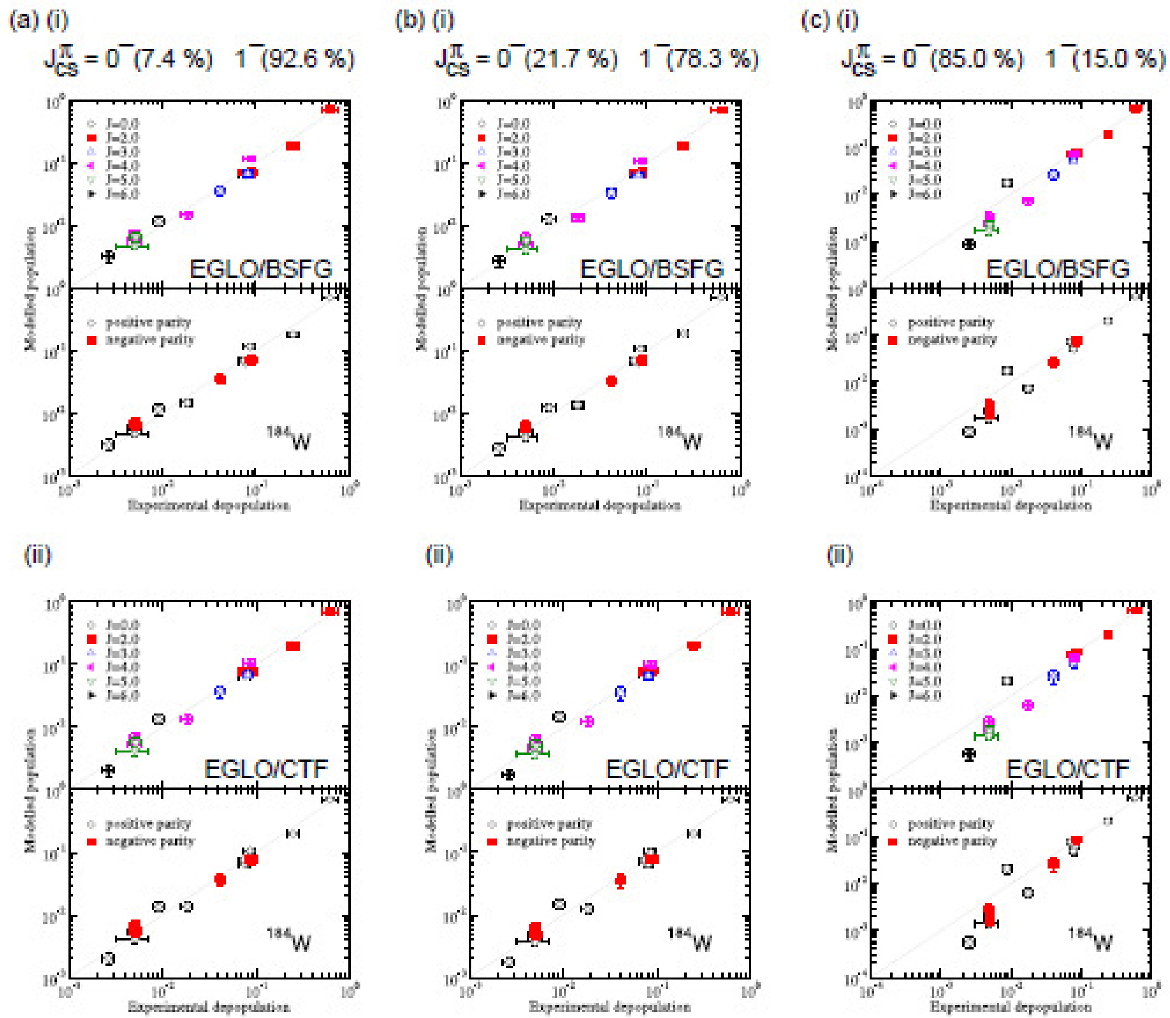
- Extract accurate normalized σ_γ
- Estimate systematic uncertainty from self attenuation using χ^2 analysis
- Measure sample thickness!



Determining the capture state: $^{183}W(n,\gamma)$

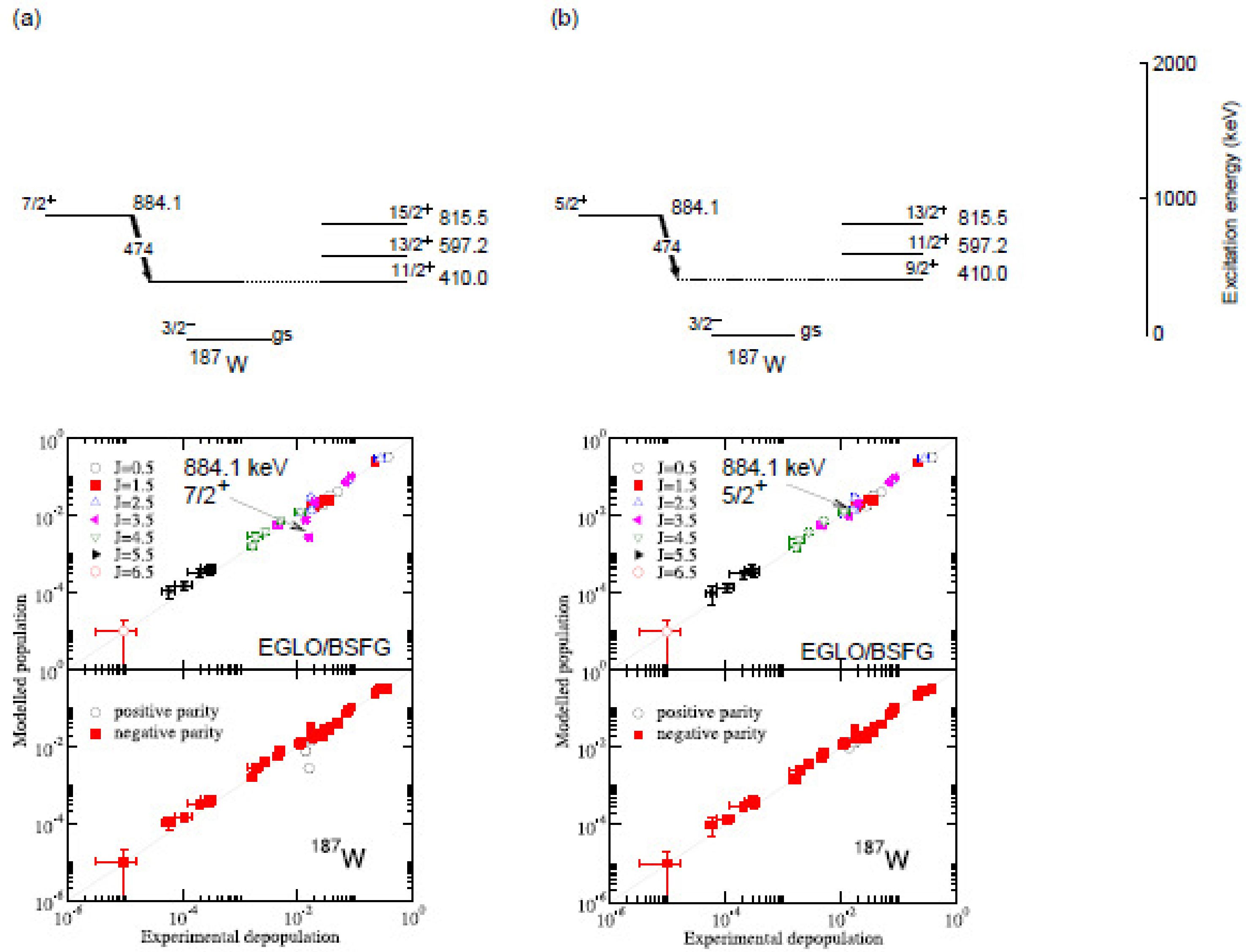
- ^{183}W G.S. $\Rightarrow J^{\pi} = \frac{1}{2}^{-}$
- ^{184}W C.S. $\Rightarrow J^{\pi} = 0^{-}$ or 1^{-} (s-wave capture)
- Atlas of Neutron Resonances $\Rightarrow \sigma_0 = 10.4(2)$ b
- $\sigma(+; 1^{-}) = 78.3$ %, $\sigma(-; 0^{-}) = 7.4$%
- Remaining 14.3 % $\Rightarrow \sigma(B)$ "bound resonance" @ -25 eV (w.r.t. neutron separation energy)
- $J^{\pi}(B)$ is unknown: either 0^{-} or 1^{-}
- Test using DICEBOX

^{184}W capture-state distributions

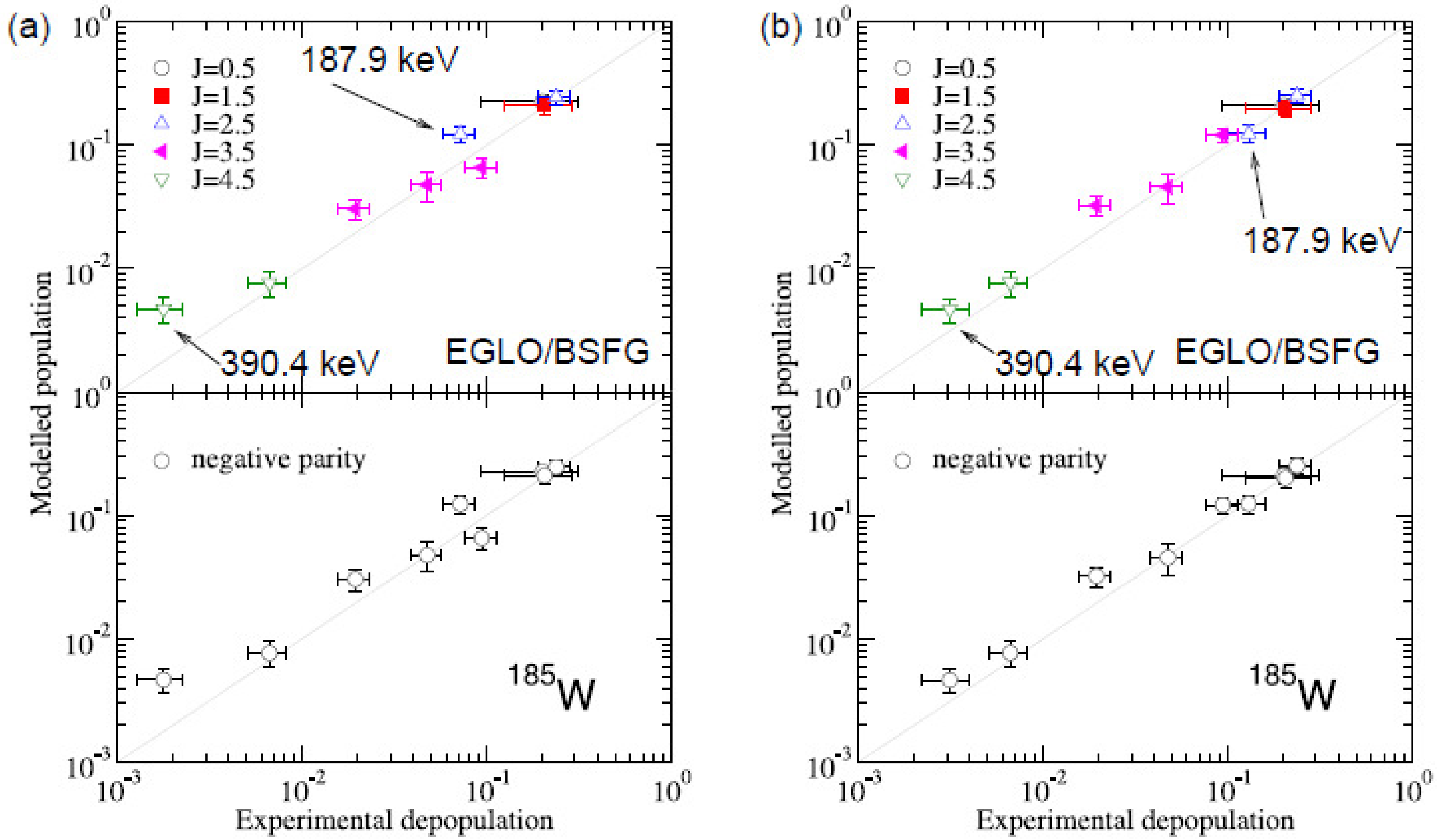


- Statistically-consistent σ_0 = 9.5(12)b [cf. σ0 = 10.4(2)]
- σ_0 not appreciable influence from PSF/LD or CS distribution

Determining J^{π}: $^{186}W(n,\gamma)$



Propose new γ rays: $^{184}W(n,\gamma)$



Summary: structural improvements for γ-ray libraries

Quantity	^{183}W	^{184}W	^{185}W	^{187}W
Primary γ rays	2	5	3	8
New γ rays	1	3	2	5
New levels	0	0	0	1
Confirmed J^{π}	3	4	3	19
Proposed J^{π}	0	0	0	5

New results to be communicated through RIPL/ENSDF

Capture-state total radiative widths

Compound	PSF/LD	Γ_0 [eV]	$\langle\Gamma_0\rangle$ [eV] (adopted)
^{183}W	EGLO/BSFG	0.072(4)	**0.051(4)**
	EGLO/CTF	**0.040(3)**	
	BA/BSFG	0.137(8)	
	BA/CTF	0.075(6)	
^{184}W	EGLO/BSFG	0.140(3)	**0.073(6)**
	EGLO/CTF	**0.073(3)**	
	BA/BSFG	0.250(6)	
	BA/CTF	0.127(5)	
^{185}W	**EGLO/BSFG**	**0.051(2)**	**0.052(4)**
	EGLO/CTF	0.034(3)	
	BA/BSFG	0.106(5)	
	BA/CTF	0.070(7)	
^{187}W	**EGLO/BSFG**	**0.058(2)**	**0.051(5)**
	EGLO/CTF	0.038(2)	
	BA/BSFG	0.126(5)	
	BA/CTF	0.081(4)	

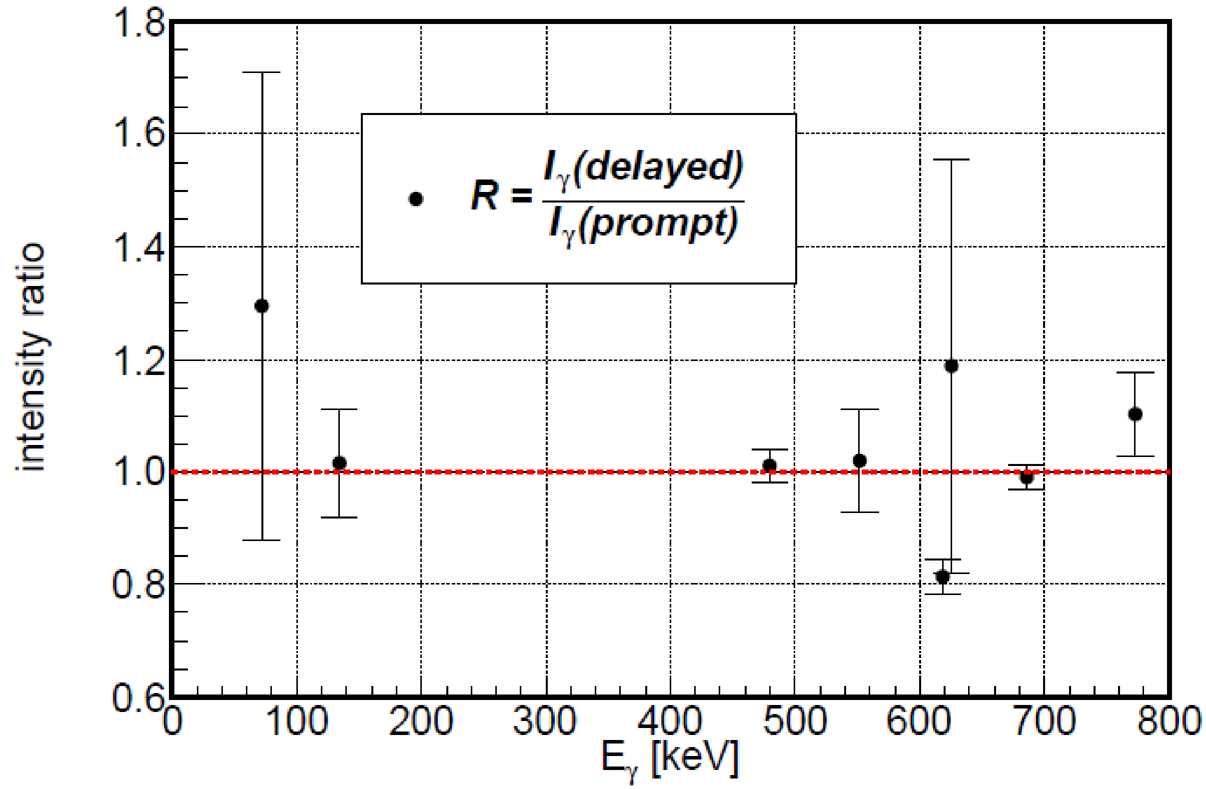
Total radiative capture cross sections for the W isotopes

$$\sigma_0 = \sum \sigma_\gamma^{\exp}(\mathrm{GS}) + \sum \sigma_\gamma^{\mathrm{sim}}(\mathrm{GS})$$

Isotope (compound)	E_{crit} [keV] RIPL-3	N RIPL-3	E_{crit} [keV] this work	N this work	σ_0 [b] adopted	σ_0 [b] this work
^{183}W: $^{182}W(n,\gamma)$	475.4	11	**480.0**	**11**	19.9(3)	**20.9(26)**
^{184}W: $^{183}W(n,\gamma)$	1252.2	12	**1370.0**	**18**	10.4(2)	**9.5(12)**
^{185}W: $^{184}W(n,\gamma)$	243.4	8	**392.0**	**12**	1.7(1)	**1.45(28)**
^{187}W: $^{186}W(n,\gamma)$	145.9	3	**900.0**	**40**	34.7(2)*	**33.0(26)**

*N. Marnada et al., J. Nucl. Sci. Tech. **36**, 1119 (1999) [4πβ-γ]
cf.:V. Bondarenko et al., Nucl. Phys. A811, 28 (2008): **σ_0 = 35.9(11) b** [(n,γ)]
S. Muhghabghab, Atlas of Neutron Resonances (2006): **σ_0 = 38.1(5) b**

P_γ measurements: $^{187}W \rightarrow {}^{187}Re + \beta^-$



E_γ [keV]	P_γ	P_γ
72.0	0.186(45)	-
134.3	0.110(11)	0.111(9)
479.5	0.288(24)	0.281(23)
551.2	0.066(5)	0.065(5)
618.0	0.076(6)	0.081(7)
625.0	0.012(1)	0.014(1)
685.7	0.350(28)	0.357(29)
773.0	0.053(5)	0.053(4)

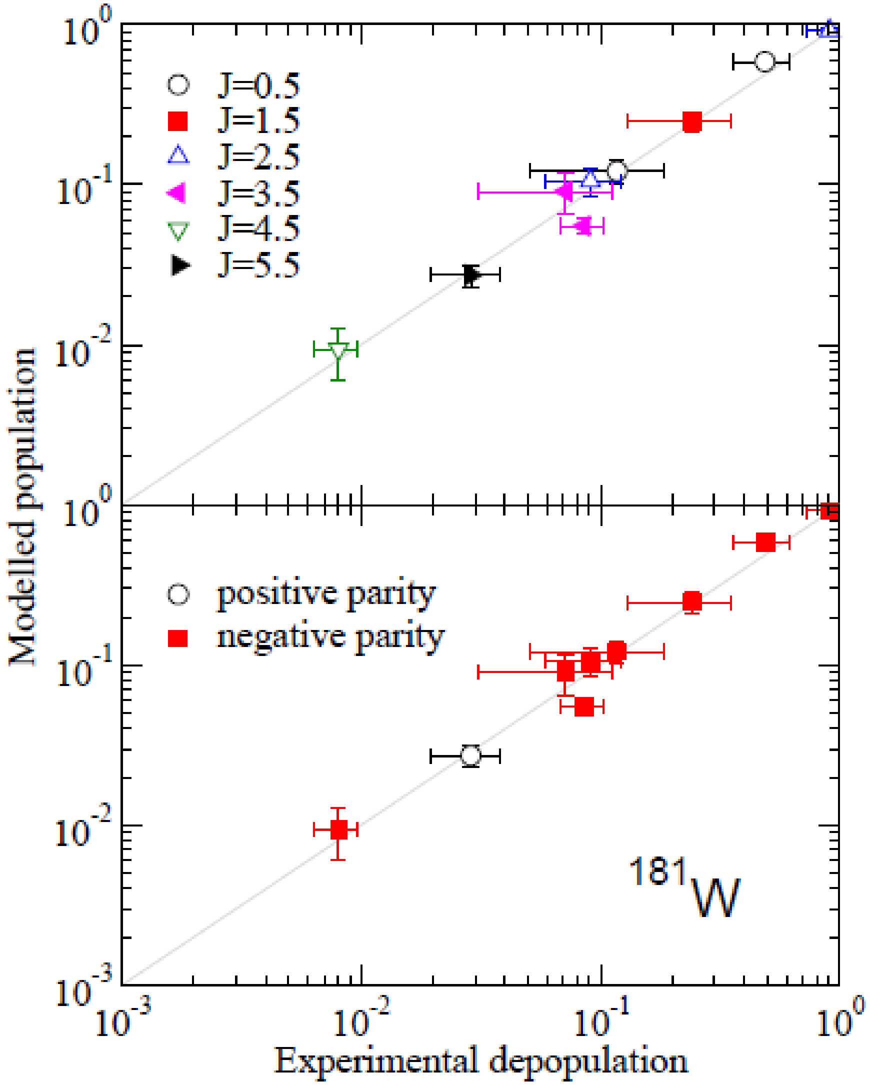
Independent confirmation of $\sigma_0(^{186}W(n,\gamma))$ = 33.0(26) b

$$P_\gamma = \frac{\sigma_\gamma}{\theta \cdot \sigma_0}$$

P_γ: This work

P_γ: L. Szentmiklosi *et al.*, NIMA 564, 655 (2006)

$^{180}W(n,\gamma)$: new measurement of σ_0



- Preliminary analysis
- Natural abundance: 0.12 %
- Ecrit ~ 528 keV (11 levels)
- S_n = 6674.0 (10) keV
  [cf. 6681(6) keV]
- σ_0 = 21.0(43) b
  [cf. 4 < σ_0 < 150 b]
- Γ_0 = 0.086 (3) eV
  [cf. 0.070(10) eV]

Summary

- Improved (and confirmed) nuclear structure and decay data for compound products of the major tungsten isotopes: ^{182}W, ^{183}W, ^{184}W, ^{186}W
- New measurements of σ_0 for each compound $\Rightarrow$ generally compare well with adopted values
- New measurements of Γ_0 for each compound $\Rightarrow$ generally compare well with adopted values
- New measurements of P_γ for β^- decay of ^{187}W $\Rightarrow$ excellent agreement with literature
- Improved databases: EGAF, ENSDF (RIPL), and ENDF (via BNL)
- **Manuscript written for Physical Review C $\Rightarrow$ current status: author review (2nd round)**
- $^{180}W(n,\gamma)$ analysis: preliminary results look promising

Collaborators

- **LBNL** – A. M. Hurst, R. B. Firestone, S. Basunia, A. M. Rogers
- **LLNL** – B. W. Sleaford, N. C. Summers, J. E. Escher
- **Budapest Reactor** – Zs. Révay, T. Belgya, L. Szentmiklósi
- **Seoul National University** – H. Choi
- **North Carolina State University** – D. Dashdorj
- **Charles University in Prague –** M. Krticka
- **IAEA** – R. Capote, A. Nichols