Lawrence Berkeley National Laboratory
Nuclear Science Division

New measurement of the radiative thermal-capture cross section for the rare isotope ^{180}W

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Cross Section Evaluation Working Group
Brookhaven National Laboratory
Upton, New York

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…)

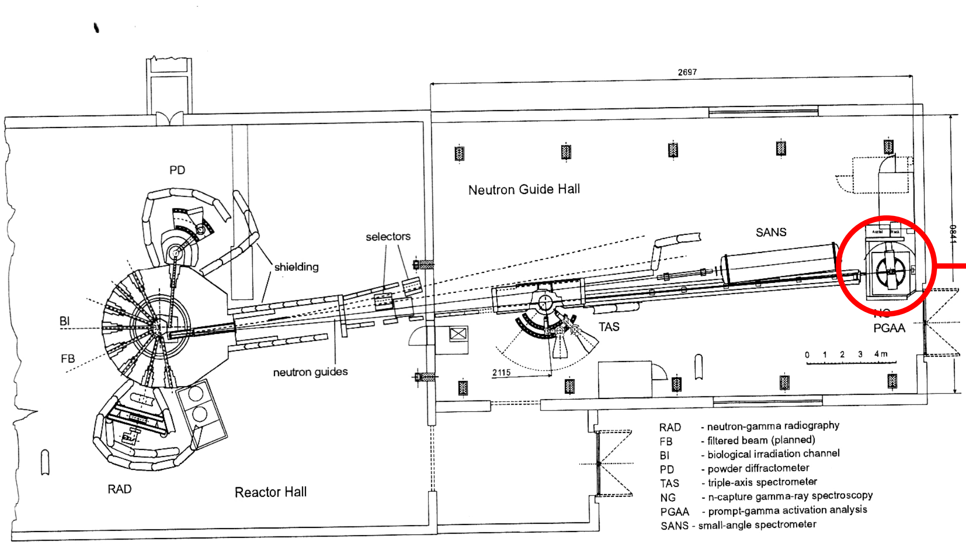
• Compare experimental data to statistical-model expectations using DICEBOX to model thermal-capture γ cascade

• Improve upon known γ-ray decay data and nuclear structure information in the **Evaluated Nuclear Structure Data File (ENSDF)**

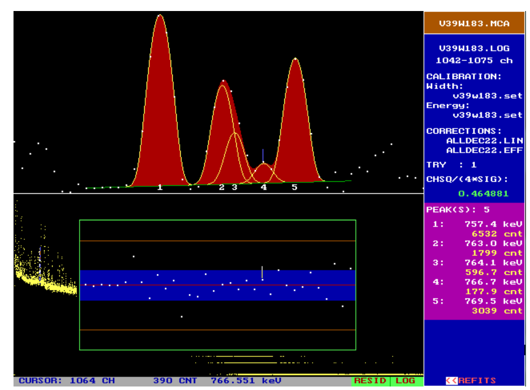
• Communicate results through the **Reference Input Parameter Library (RIPL)** in addition to the **Evaluated Nuclear Data File (ENDF)** neutron-data library

• Ultimately: part of a complete library to be disseminated through BNL

EGAF data measured @ Budapest Reactor

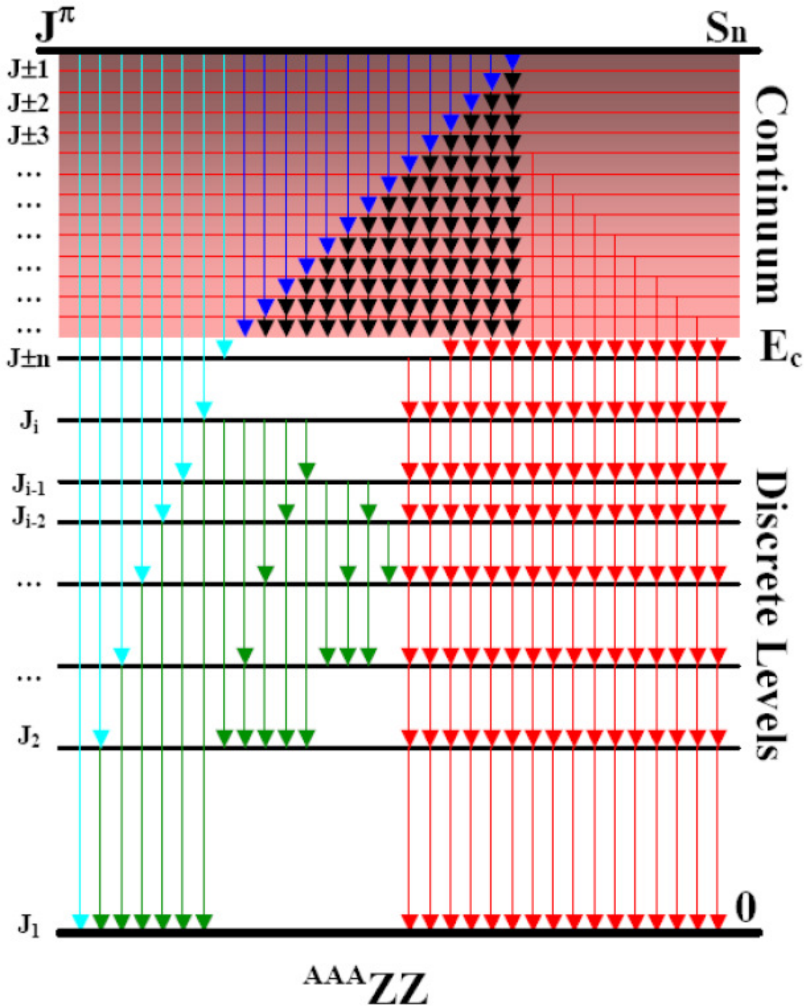


- 10 MW Budapest reactor
- Thermal flux ~ 10^6 $cm^{-2}s^{-1}$
  Cold flux ~ 10^8 $cm^{-2}s^{-1}$
- PGAA (Prompt Gamma Activation Analysis) facility ~ 35 m from reactor wall (low background)
- Compton-suppressed HPGe detector (closed-end coaxial) located 23.5 cm from target
- HYPERMET: analysis tool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



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.

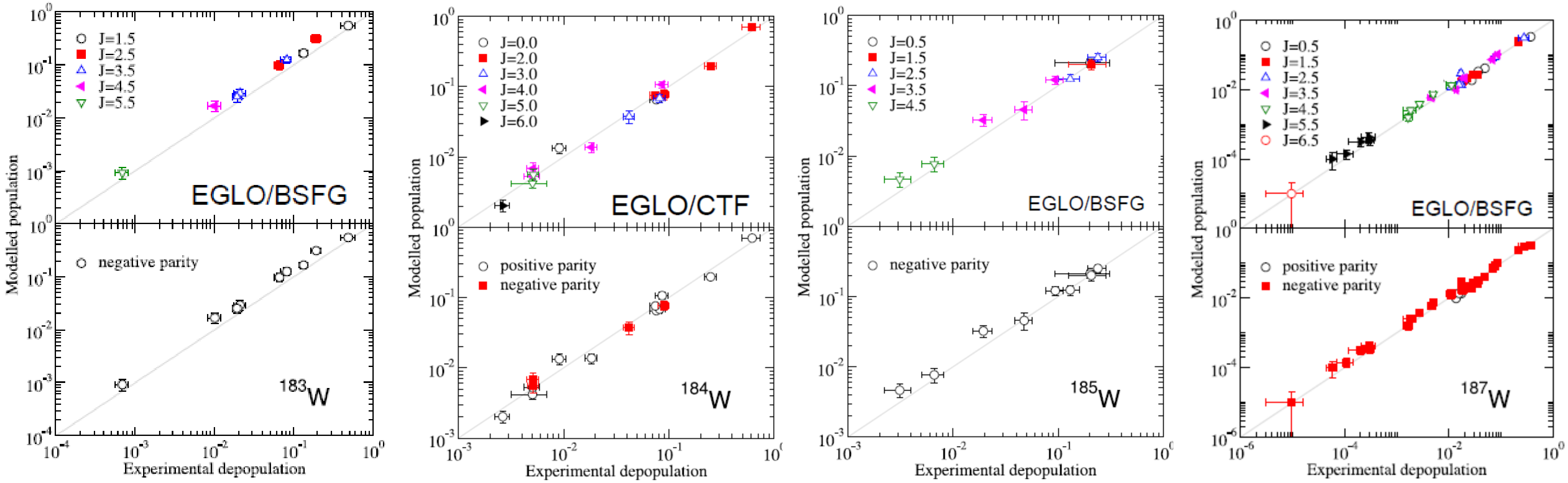
b) All levels and γ-rays above E_{crit} are generated randomly from level density and PSF models

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.

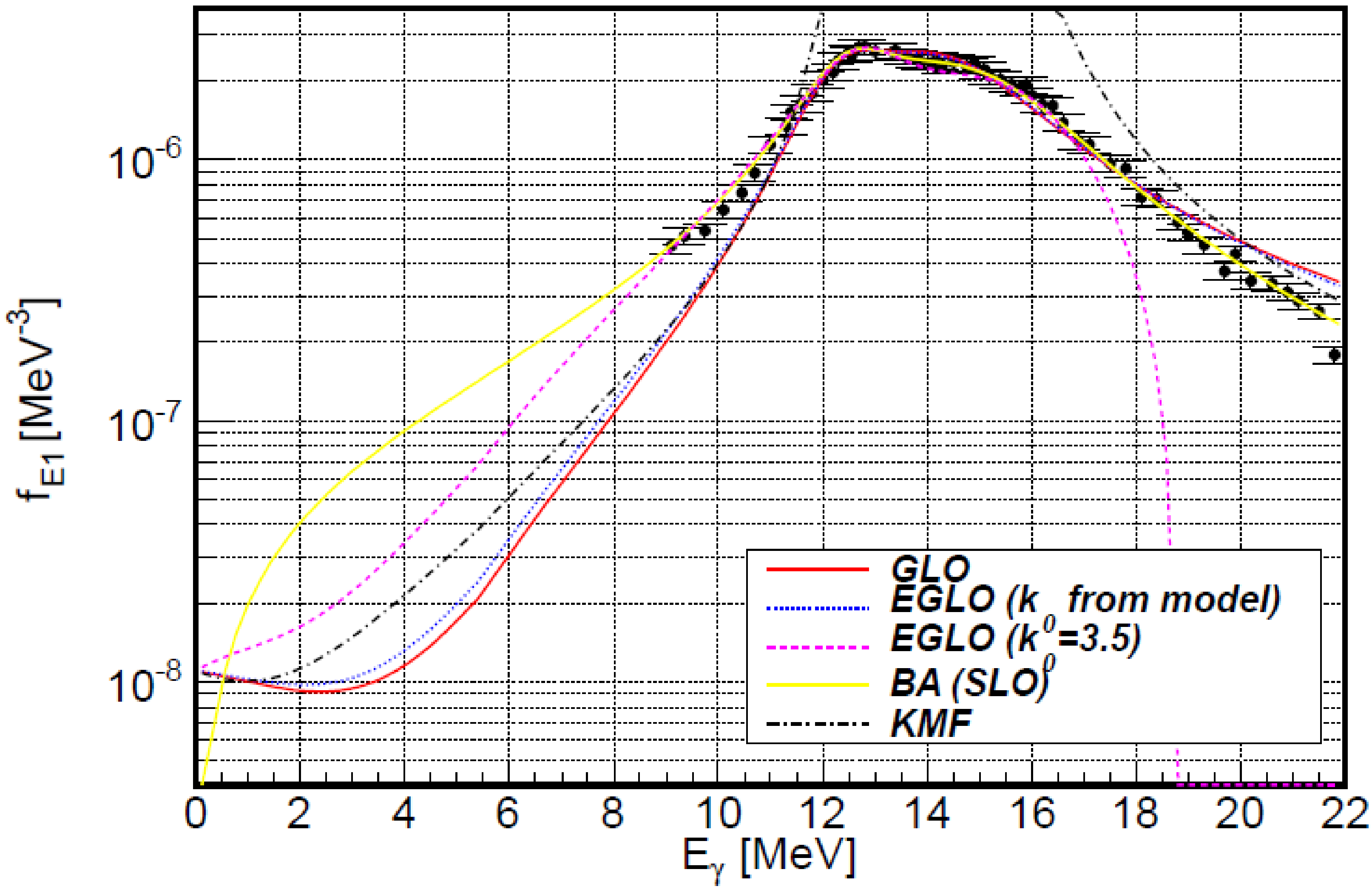
Modeling W isotopes using DICEBOX



$^{182}W(n,\gamma)^{183}W$	$^{183}W(n,\gamma)^{184}W$	$^{184}W(n,\gamma)^{185}W$	$^{186}W(n,\gamma)^{187}W$
E_{crit} = 480 keV	E_{crit} = 1370 keV	E_{crit} = 392 keV	E_{crit} = 900 keV

Final results: complete information on nuclear energy levels

Determining the PSF



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

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

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,γ)	475.4	11	**480.0**	**11**	19.9(3)	**20.9(26)**
^{184}W: ^{183}W(n,γ)	1252.2	12	**1370.0**	**18**	10.4(2)	**9.5(12)**
^{185}W: ^{184}W(n,γ)	243.4	8	**392.0**	**12**	1.7(1)	**1.45(28)**
^{187}W: ^{186}W(n,γ)	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)]

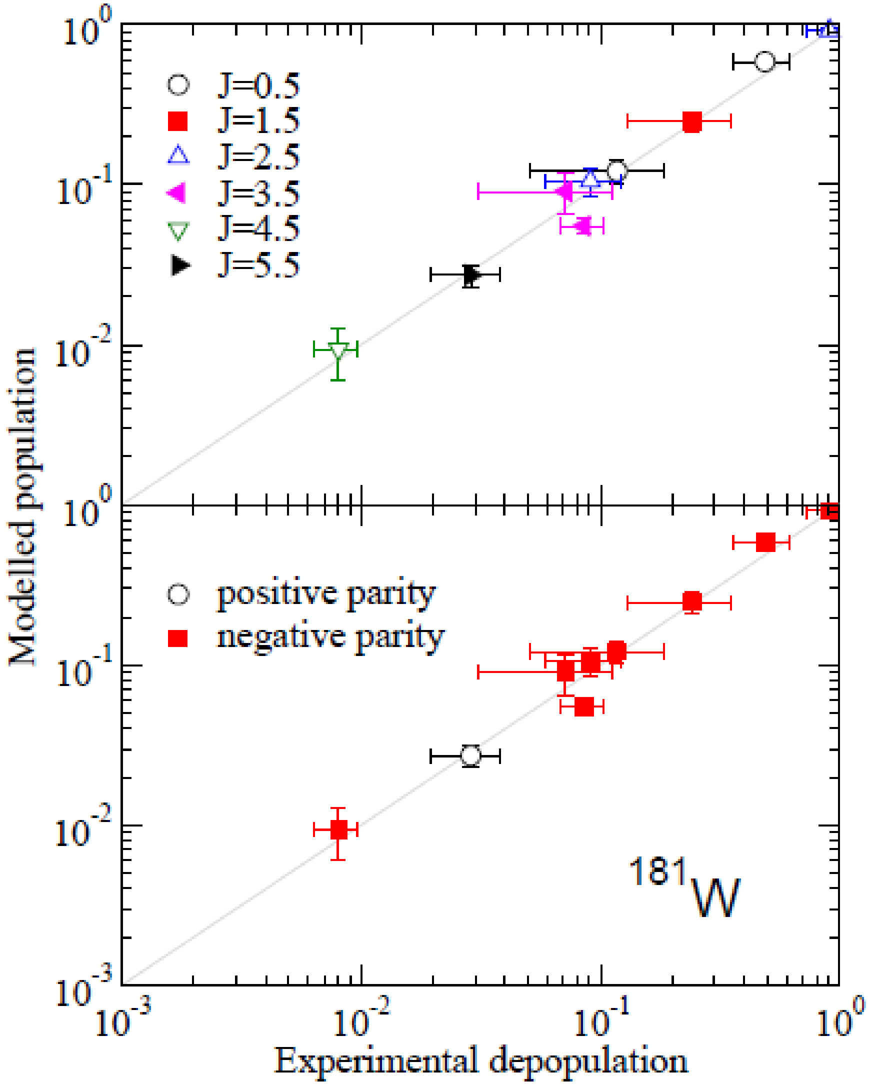
S. Muhghabghab, Atlas of Neutron Resonances (2006): **σ_0 = 38.1(5) b**

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

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

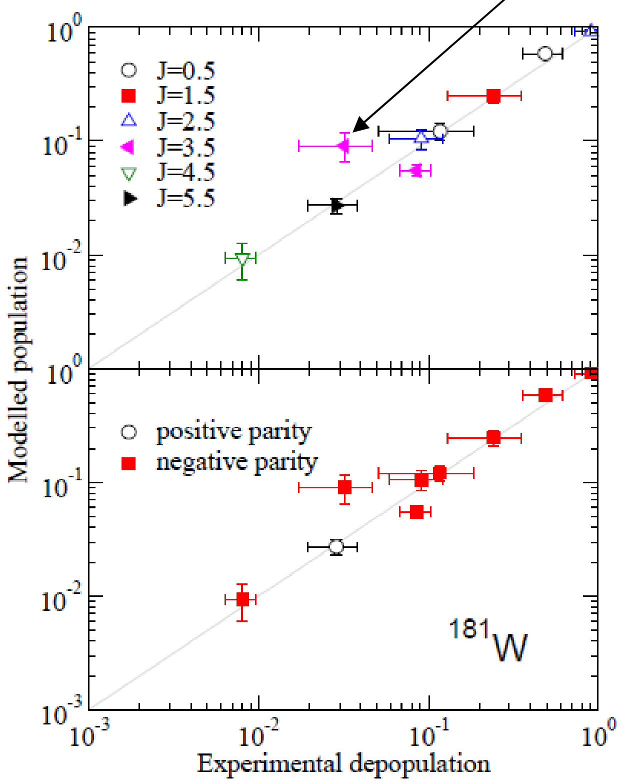


- Preliminary analysis
- Natural abundance: 0.12 %
- 11.35 % enriched sample
- Ecrit ~ 528 keV (11 levels)
- S_n = 6674.0 (10) keV
  [cf. 6681(6) keV]
- σ_0 = 21.0(43) b
  [cf. 4 < σ_0 < 150 b]
- Γ_0 = 0.086 (3) eV
  [cf. 0.070(10) eV]

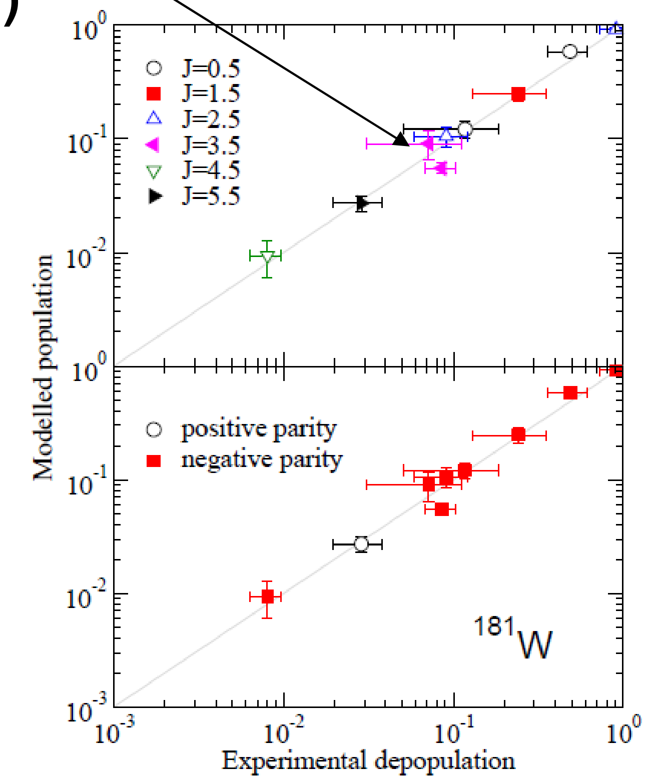
Determining δ_γ for mixed *M1+E2* transitions

E_L = 409.2 keV

(E_γ = 43.5 keV)

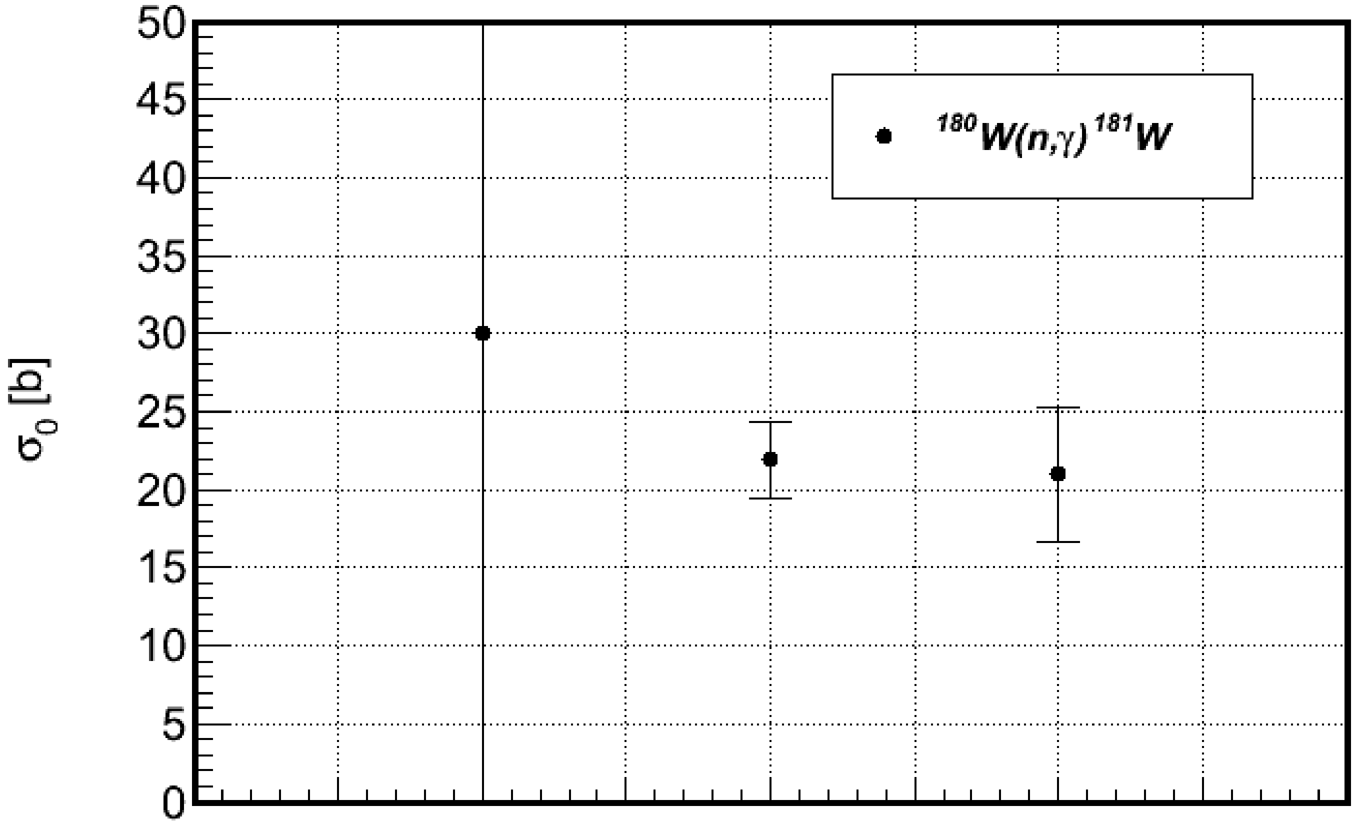


- δ_γ = 0.10 (ENSDF)
- α = 10.7 (*E2* ⇒ 1 %)



- δ_γ = 0.49 (ENSDF)
- α = 39.2 (*E2* ⇒ 19 %)

σ_0: $^{180}W(n,\gamma)$



1952 **2008** **2012**

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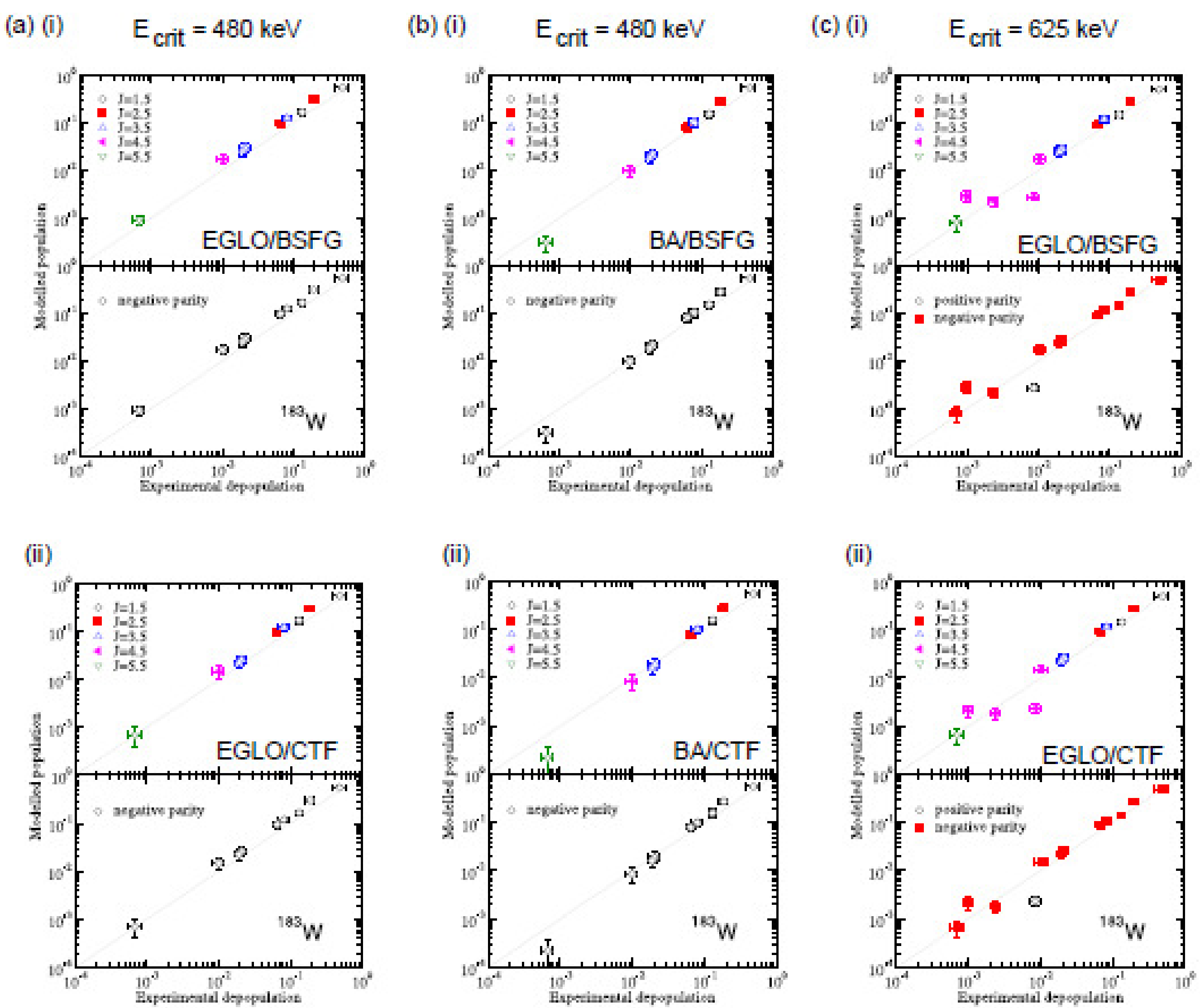
Summary

- 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,γ) 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

Analysis of $^{182}W(n,\gamma)$



The issue with γ-ray self attenuation

- For dense materials (e.g. W) $\Rightarrow$ 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	→

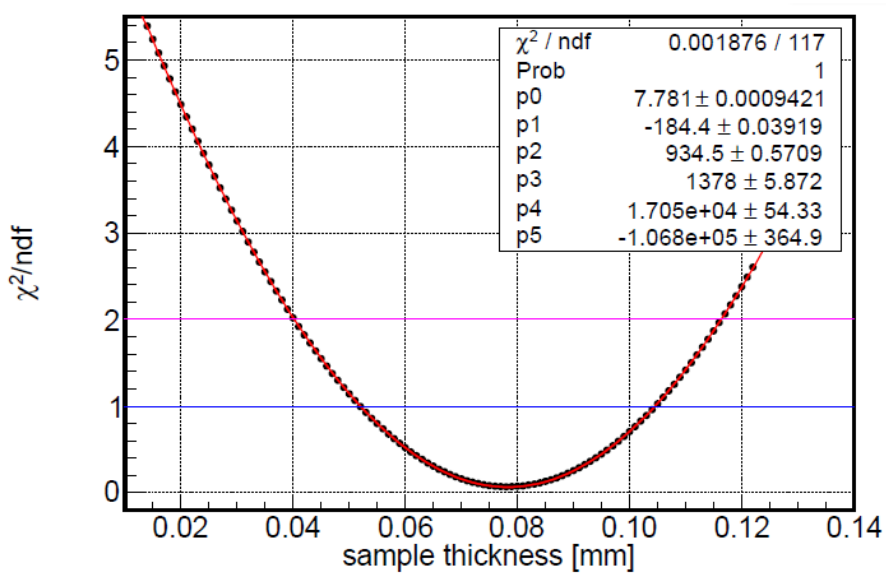
e.g. ^{186}W

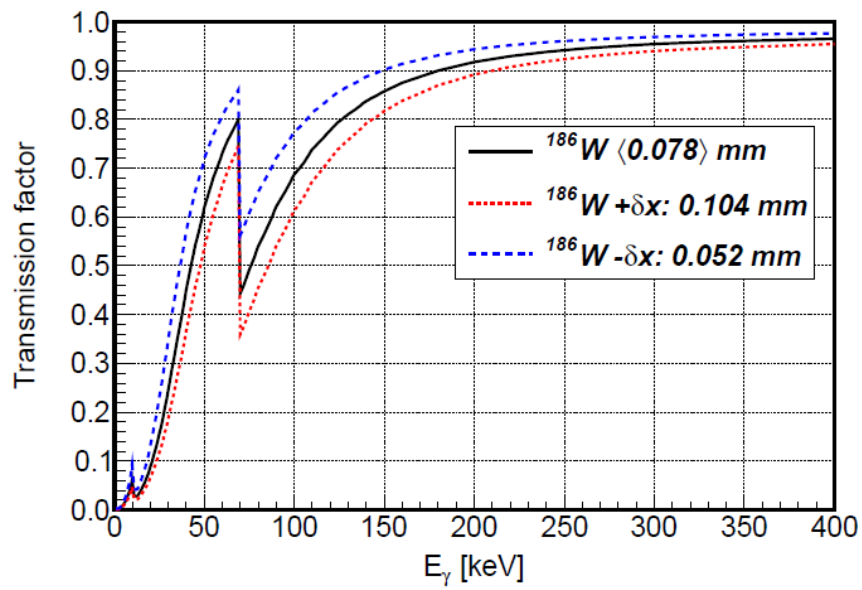
0.078 mm

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!

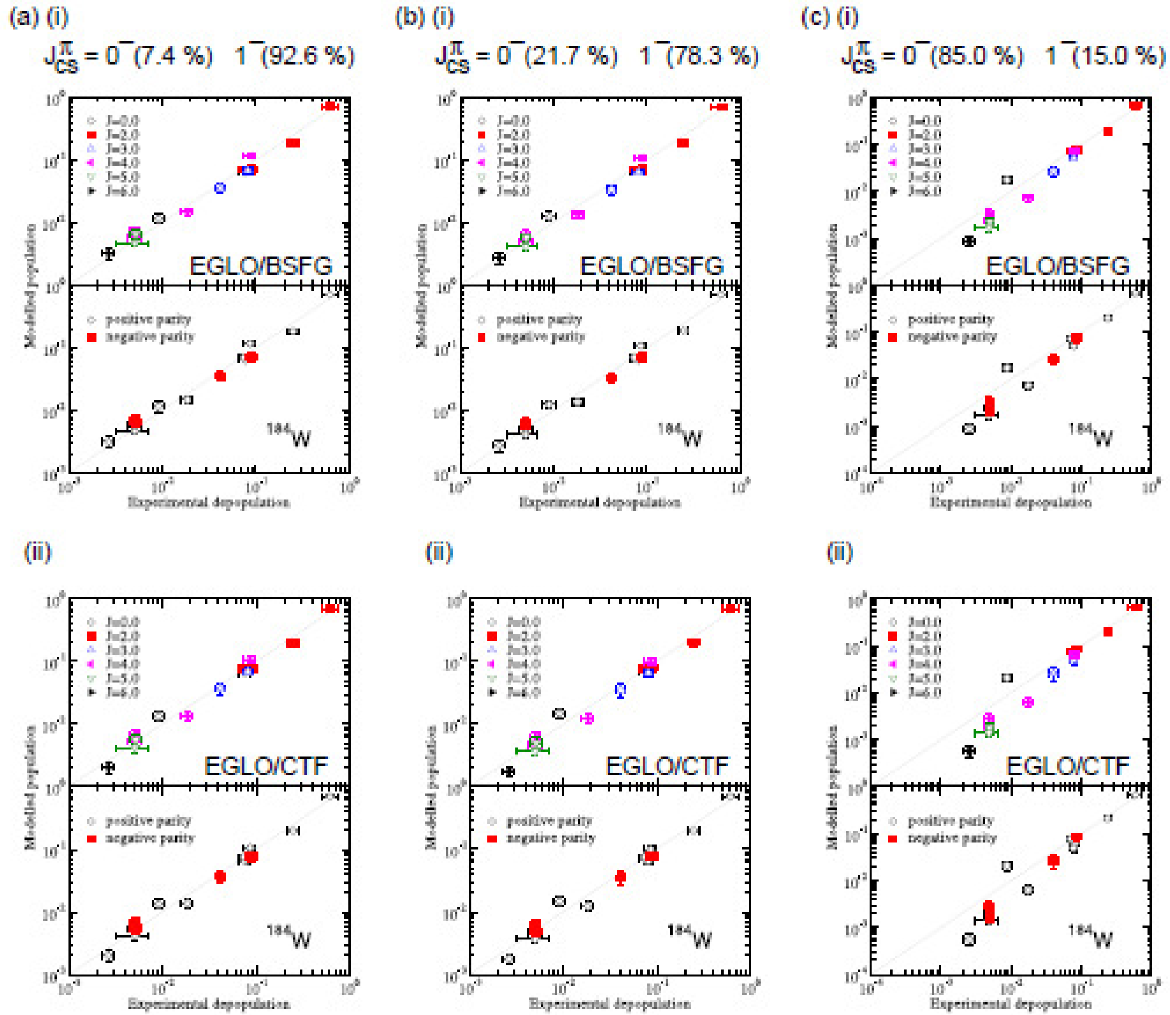




Determining the capture state: $^{183}W(n,\gamma)$

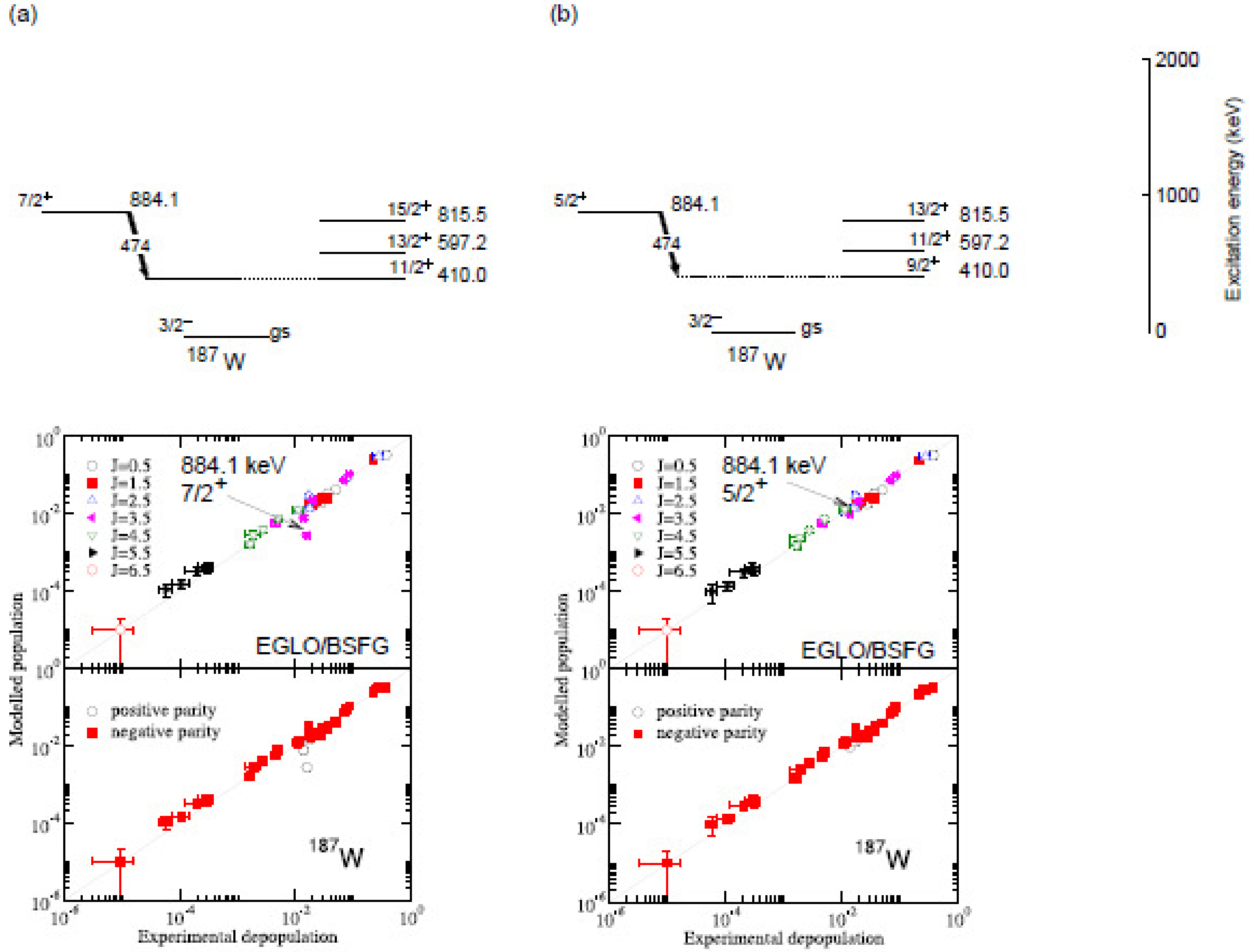
- ^{183}W G.S. $\Rightarrow J^{\pi} = ½^{-}$
- ^{184}W C.S. $\Rightarrow J^{\pi} = 0^{-}$ or 1^{-} (s-wave capture)
- Atlas of Neutron Resonances $\Rightarrow \sigma_0 = 10.4(2)$ b
- $\sigma(+; 1^{-}) = 78.3$ %, $\sigma(-; 0^{-}) = 7.4$%
- Remaining 14.3 % $\Rightarrow \sigma(B)$ "bound resonance" @ -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

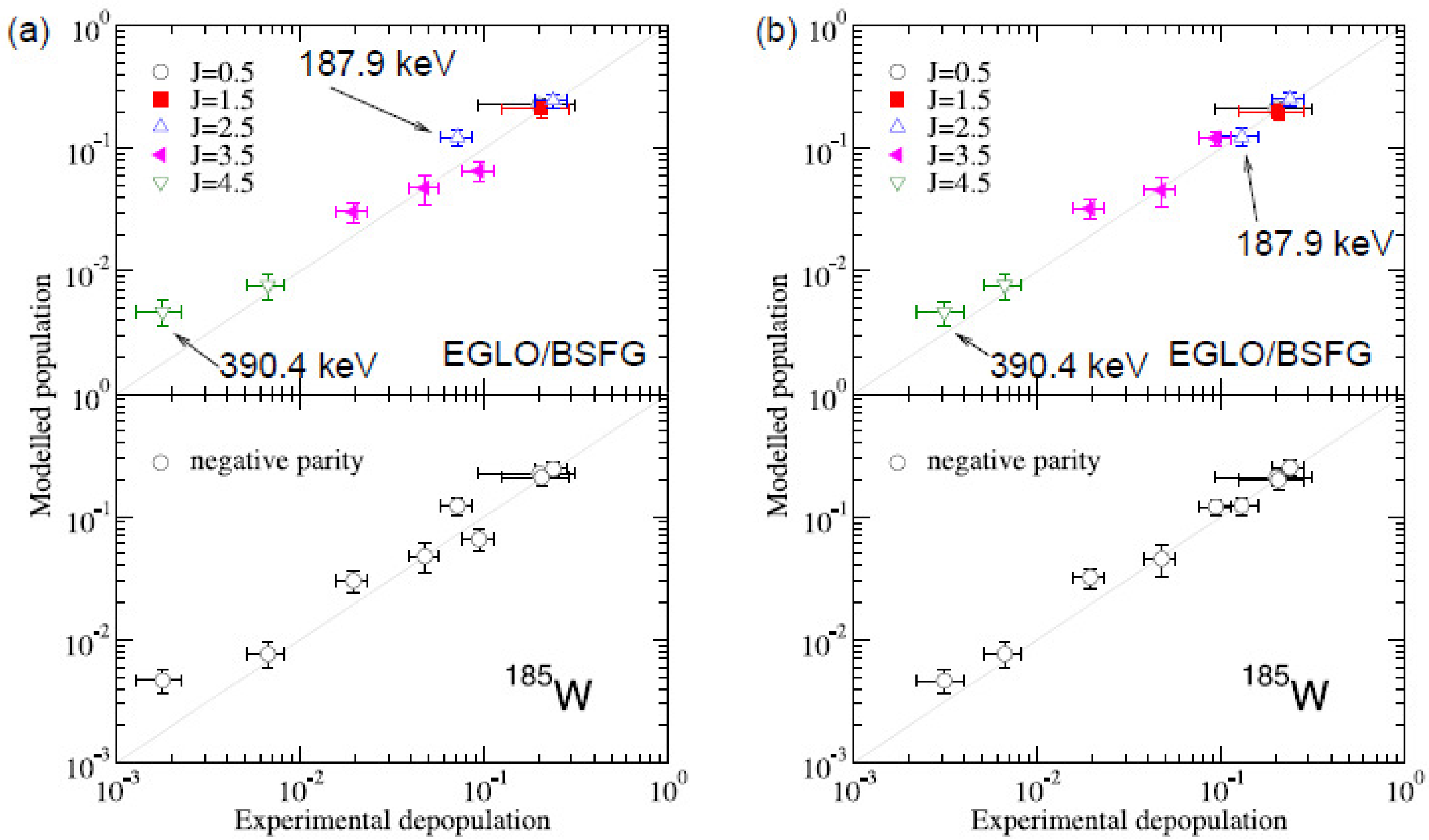


- Statistically-consistent σ_0 = 9.5(12)b [cf. σ0 = 10.4(2)]
- σ_0 not appreciable influence from PSF/LD or CS distribution

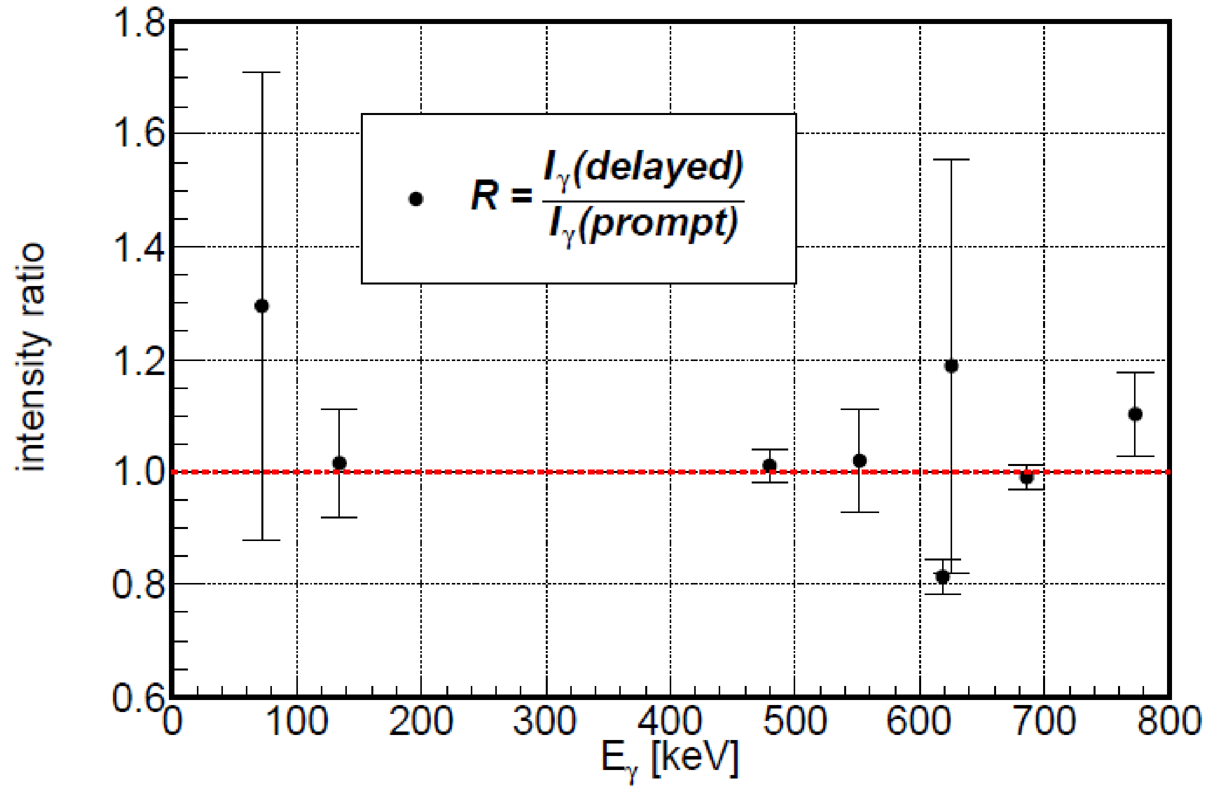
Determining J$^{\pi}$: ^{186}W(n,γ)



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



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)