Lawrence Berkeley National Laboratory
Nuclear Science Division

Thermal neutron-capture cross sections of the tungsten isotopes

Aaron M. Hurst
AMHurst@lbl.gov

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Improving the neutron-capture γ-ray spectrum

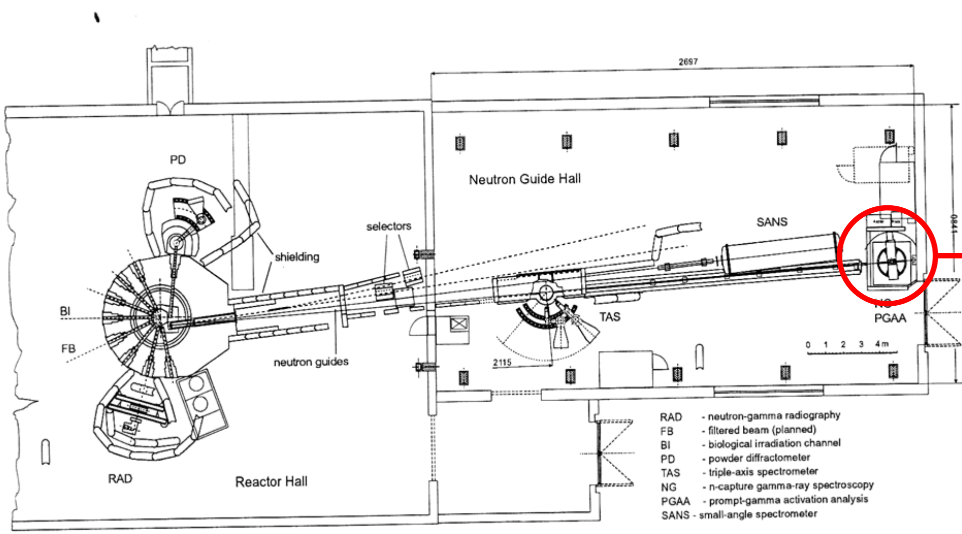
▪ Goal

- Total radiative thermal neutron-capture cross sections (σ_0)
- Improve nuclear structure information on the W isotopes and build upon spectrum of known W γ rays in neutron data libraries
- Improvements to the **Evaluated Gamma-ray Activation File** (EGAF) and **Evaluated Nuclear Structure Data File** (ENSDF) databases, and reformatted **Reference Input Parameter Library** (RIPL)

▪ Method

- Thermal neutron capture on samples of separated W (≥98%) isotopes
- Use the statistical-decay code DICEBOX to model thermal-capture γ cascade and tune input parameters to experimental data from the analyzed capture-γ spectrum

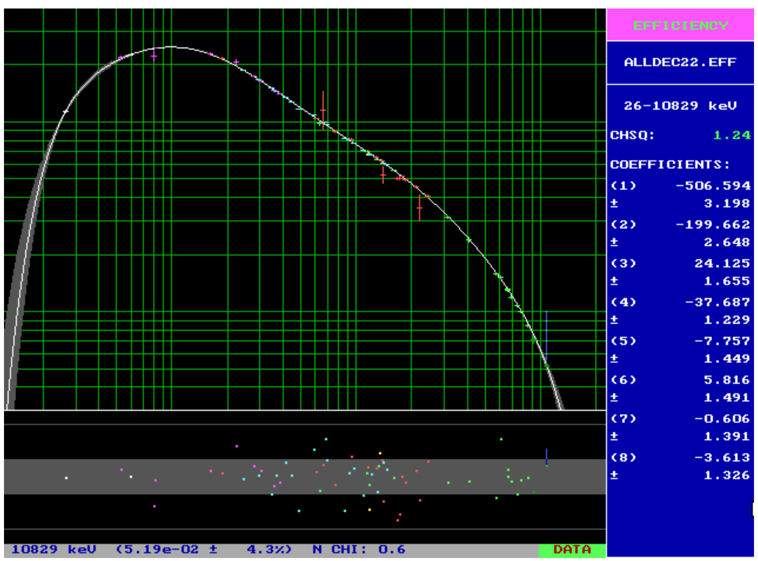
Neutron capture onto W @ Budapest Reactor

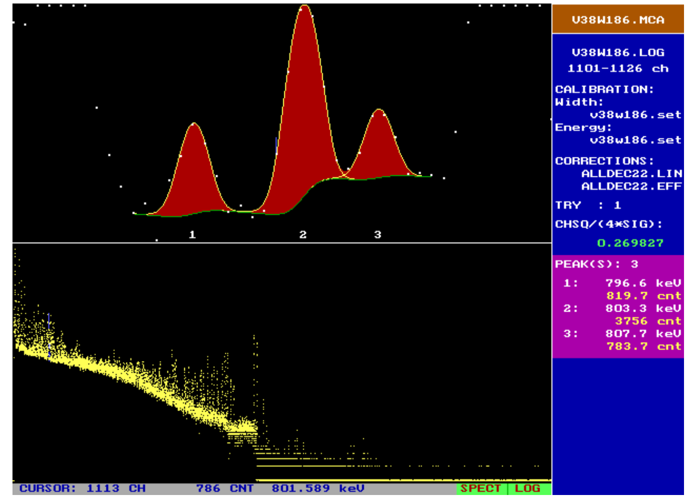


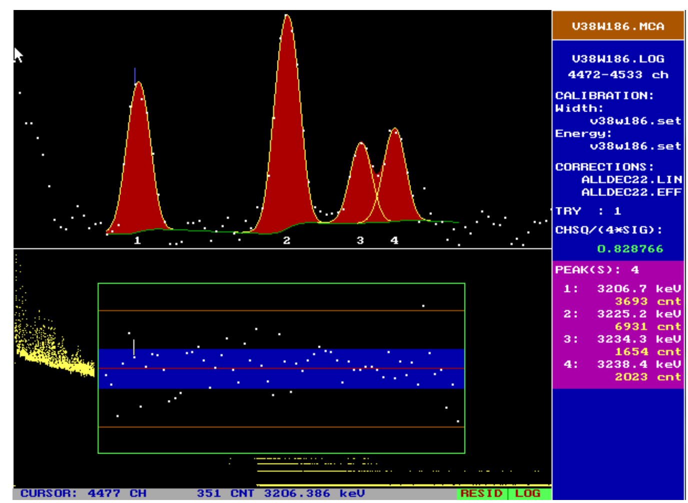
- 10 MW Budapest reactor
- Guided-thermal neutron beam:
  thermal flux ~ 10^6 $cm^{-2}s^{-1}$
  cold flux ~ 10^8 $cm^{-2}s^{-1}$
- Separated W samples ~ few 100 mg
- PGAA (Prompt Gamma Activation Analysis) experimental station is located ~ 30 m from reactor wall
- Primary and secondary capture γ rays measured in low-background
- Compton-suppressed HPGe detector (closed-end coaxial) located 23.5 cm from target

Spectroscopy of separated W samples

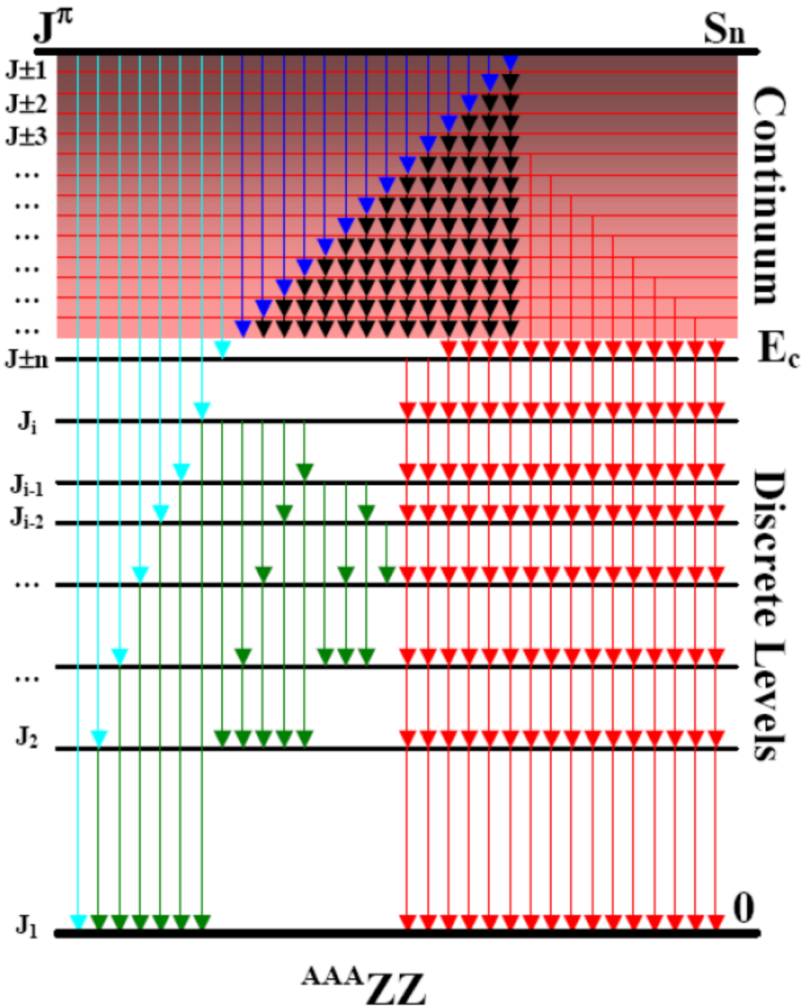
- HYPERMET: γ-ray spectroscopy
- 50 keV ~ 10 MeV
- E.g. $^{186}W(n,\gamma)^{187}W \Rightarrow$ ~ 700 peaks!
- Complex spectra
- ^{133}Ba, ^{152}Eu, ^{35}Cl [PVC], ^{226}Ra, ^{14}N[Urea]







DICEBOX Monte Carlo Code



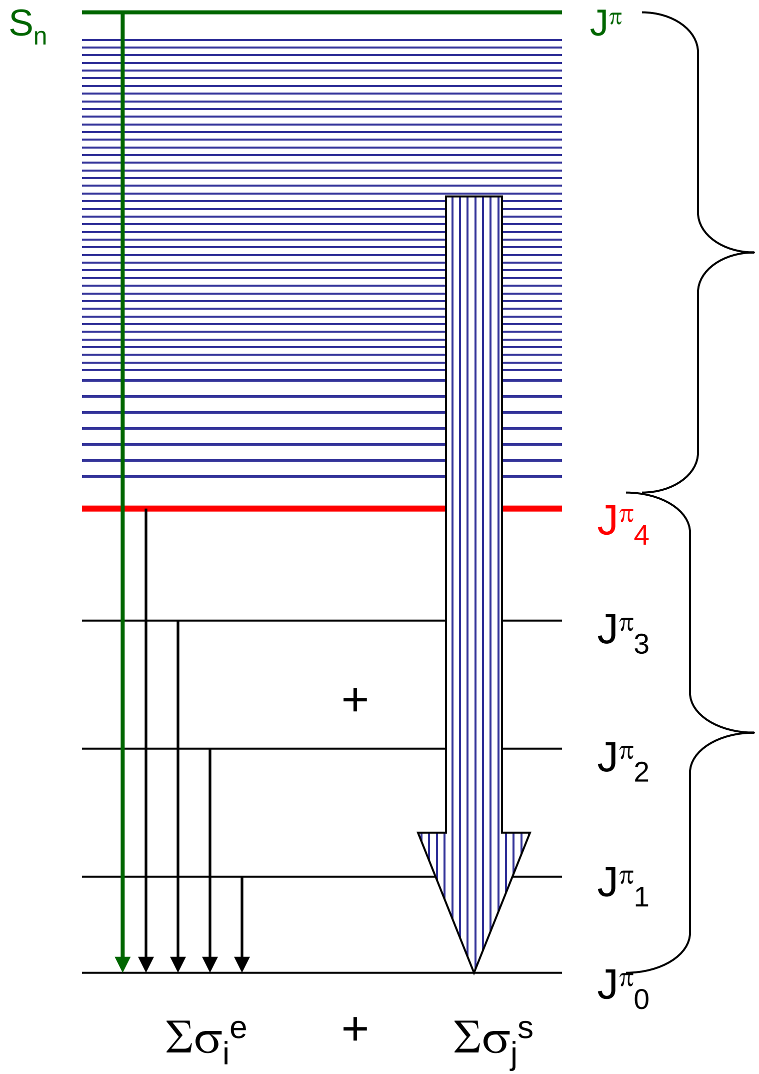
DICEBOX generates (n,γ) level scheme simulations (nuclear realizations) based on statistical model level densities $\rho(E_i, J^{\pi}_i)$ and γ-ray transition probabilities Γ_{if} where

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.

Total capture cross section



- New thermal neutron capture cross sections, σ_0
- Sum of
  - Measured experimental gamma cross sections which feed the ground state (primary+feeding below E_{crit}) ($\Sigma\sigma_i^e$)
  - Modeled population feeding from continuum to ground state ($\Sigma\sigma_j^s$)
- $\sigma_0 = \Sigma\sigma_i^e + \Sigma\sigma_j^s$

Evaluation of the W isotopes

Stable tungsten occurs naturally in 5 isotopic forms:

- ^{180}W (0.12%) very little (n,γ) information, not considered in evaluation
- ^{182}W (26.50%)
- ^{183}W (14.31%)
- ^{184}W (30.64%)
- ^{186}W (28.43%)

Stable $^{182-186}W$ all have large natural abundances, therefore, evaluation is needed for all isotopes

For all W data evaluations:

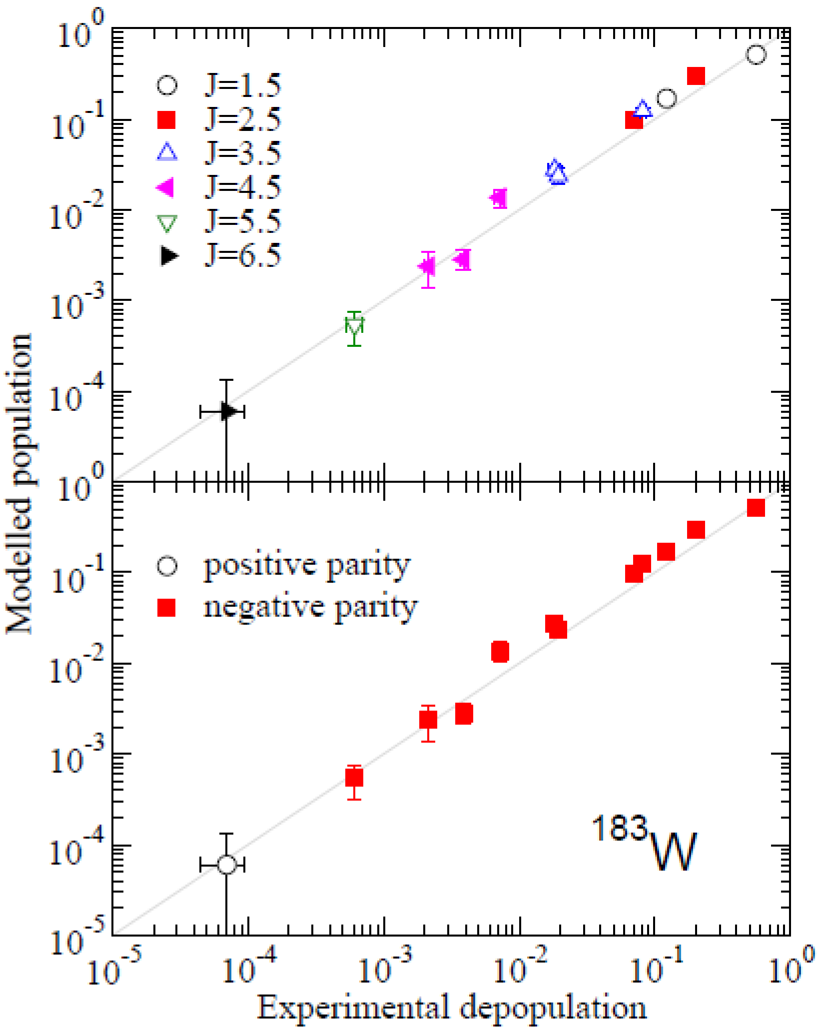
consider compound system i.e. $^{A}W(n,\gamma)^{A+1}W$

^{A+1}W is the compound system

calculations assuming 10 nuclear realizations, with 50,000 capture-state γ-ray decay cascades generated per realization

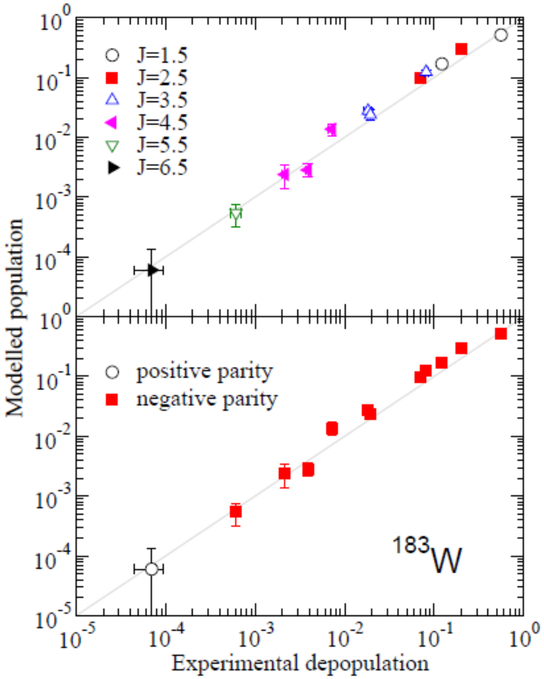
Results: $^{182}W(n,\gamma)^{183}W$

- Population (Simulation) – depopulation (Experiment) plots
- **Population ≈ depopulation**
- Level scheme information is accurate and complete
- Statistical model explains observed levels
- **Population ≠ depopulation**
- Missing or inaccurate information in the level scheme
- γ rays (and their branching ratios), levels, J^{π} assignments
- Plot shows good agreement between experiment and theory for ^{183}W compound
- E_{crit} = 595.7 keV, 16 low-lying levels



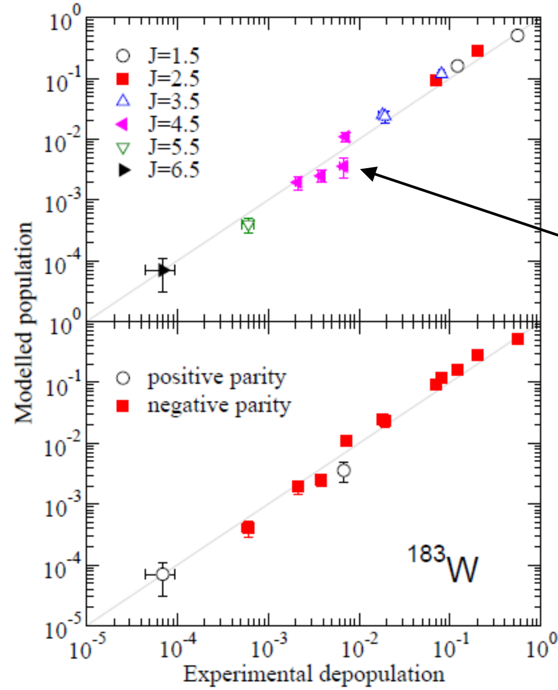
Determining the critical energy E_{crit}

E_{crit} = 595.7 keV



- 16 low-lying levels
- σ_0 = 20.28(95) b

E_{crit} = 622.2 keV

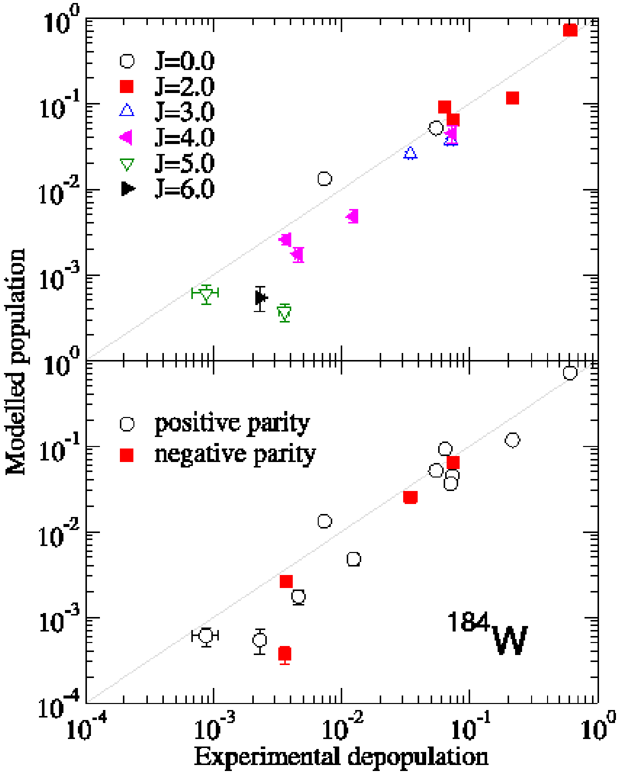


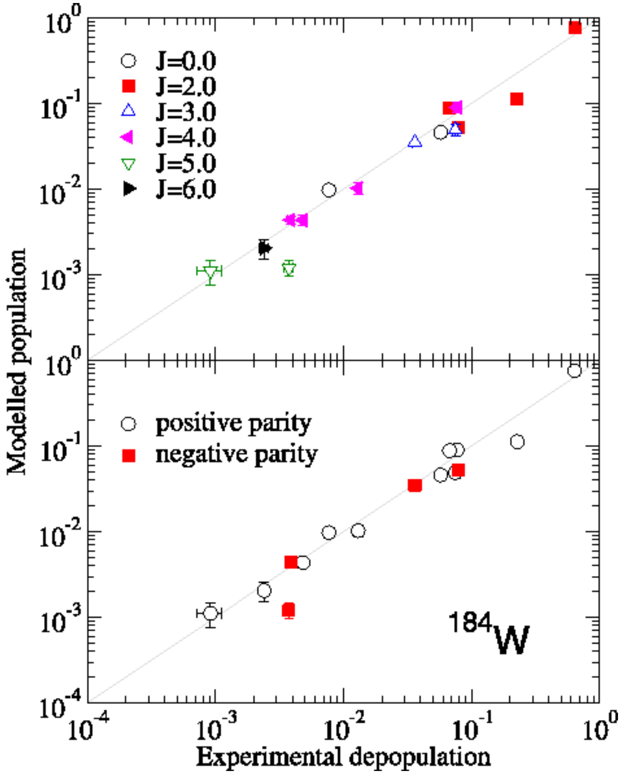
622.2-keV $9/2^-$ state

- 17 low-lying levels
- σ_0 = 20.5(11) b
- How to establish E_{crit}?
- Isomers, unobserved levels, gammas, statistically-signifcant deviation of data

Results: $^{183}W(n,\gamma)^{184}W$

Determining the spin (J^{π}) composition of the neutron-capture state



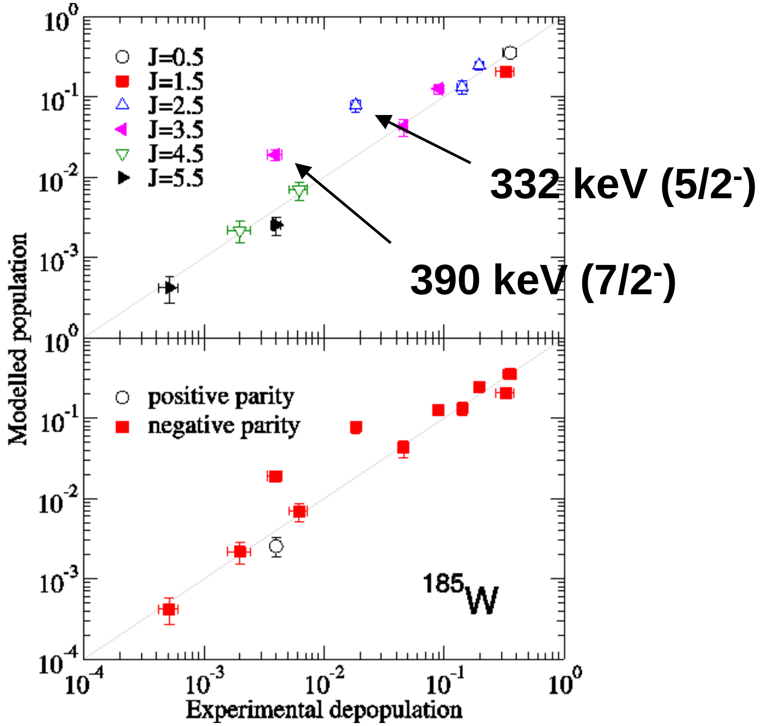


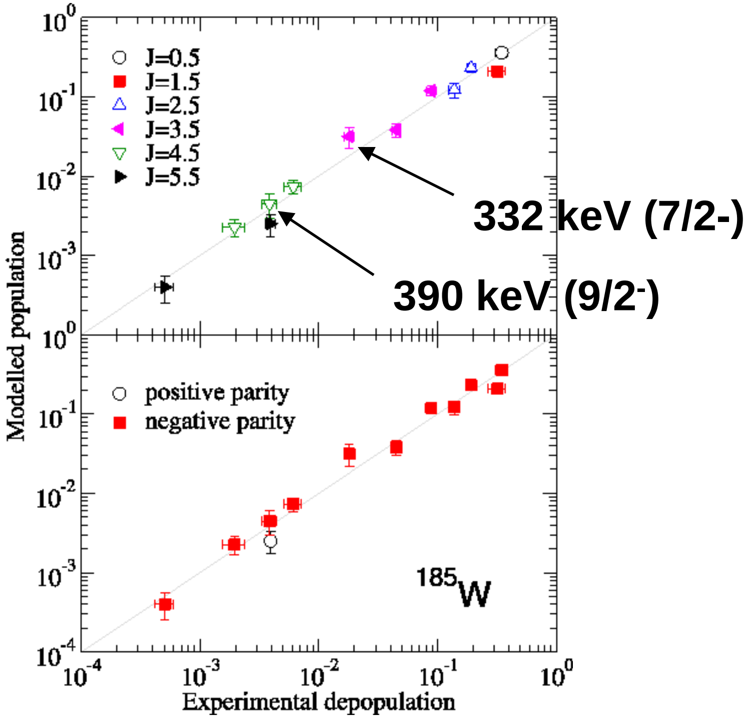
- 80% [0-], 20% [1-]
- Poor fit

- 10% [0-], 90%[1-]
- cf. Muhghabghab (2006)
- Good fit

Results: $^{184}W(n,\gamma)^{185}W$

Improving the nuclear structure: determining J^{π} of low-lying states

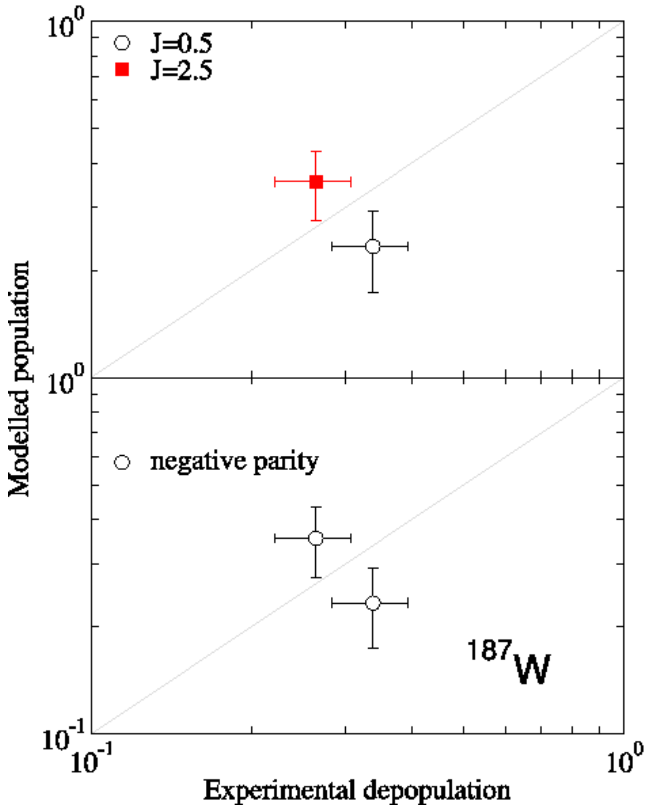


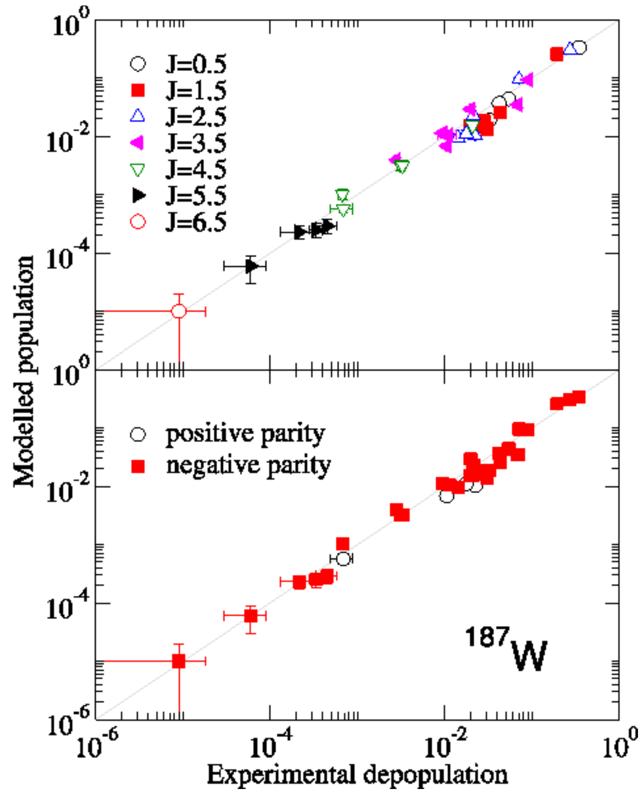


- Poor J^{π} assignment
- Good J^{π} assignment

Results: $^{186}W(n,\gamma)^{187}W$

Raising the critical energy (E_{crit})





- RIPL: suggested E_{crit} = 145.8 keV
- 3 low-lying levels

- DICEBOX analysis: E_{crit} = 891.9 keV
- 41 low-lying levels

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] [# levels]	σ_0 [b] adopted	σ_0 [b] this work
^{183}W: $^{182}W(n,\gamma)$	622.2 [17]	19.9(3)	20.5(11)
^{184}W: $^{183}W(n,\gamma)$	1360.4 [18]	10.4(2)	10.44(41)
^{185}W: $^{184}W(n,\gamma)$	492.0 [14]	1.7(1)	1.15(10)
^{187}W: $^{186}W(n,\gamma)$	891.9 [41]	42.1(7)*	43.2(12)

***** Muhghabghab (2006): σ_0 = 38.1(5) b

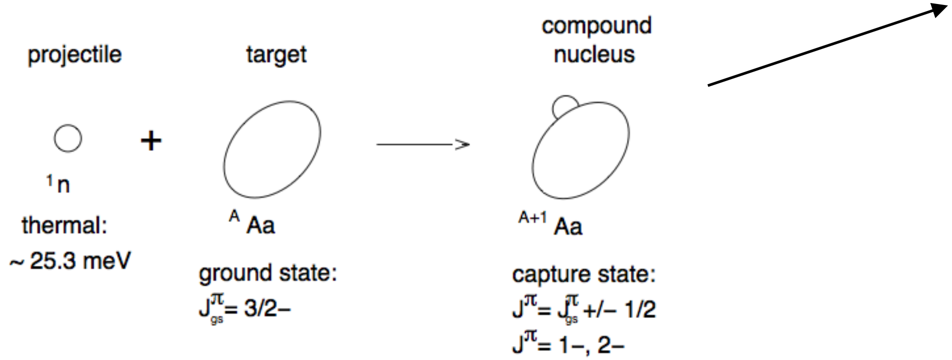
Summary and outlook

- DICEBOX: useful tool for simulating γ-ray emission following thermal neutron capture on the W isotopes
- Spectroscopy of W isotopes through thermal neutron capture on isotopically-enriched samples elucidates a better understanding of the level schemes
- Analysis of compound systems: ^{183}W, ^{184}W, ^{185}W, ^{187}W is largely complete with improved levels schemes (γ rays, levels, branching ratios, J^{π} assignments)
- Improved databases: EGAF and ENSDF (RIPL)
- New independent measurements of the total radiative thermal neutron-capture cross section for each of the W isotopes
- Forthcoming publication targeted at PRC
- Future: ^{180}W (~11%) – recently measured at the Budapest Reactor

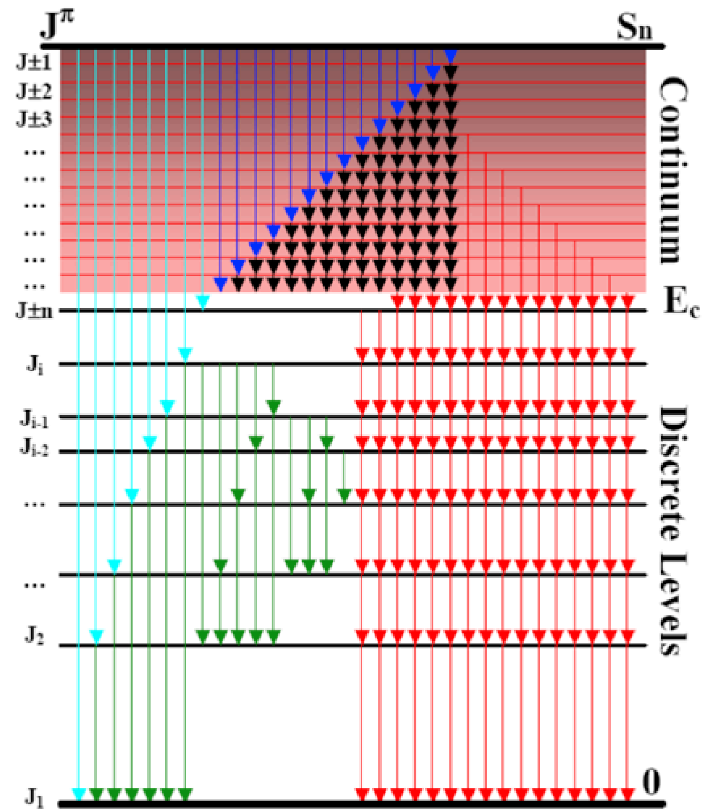
Collaborators

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

Thermal neutron capture



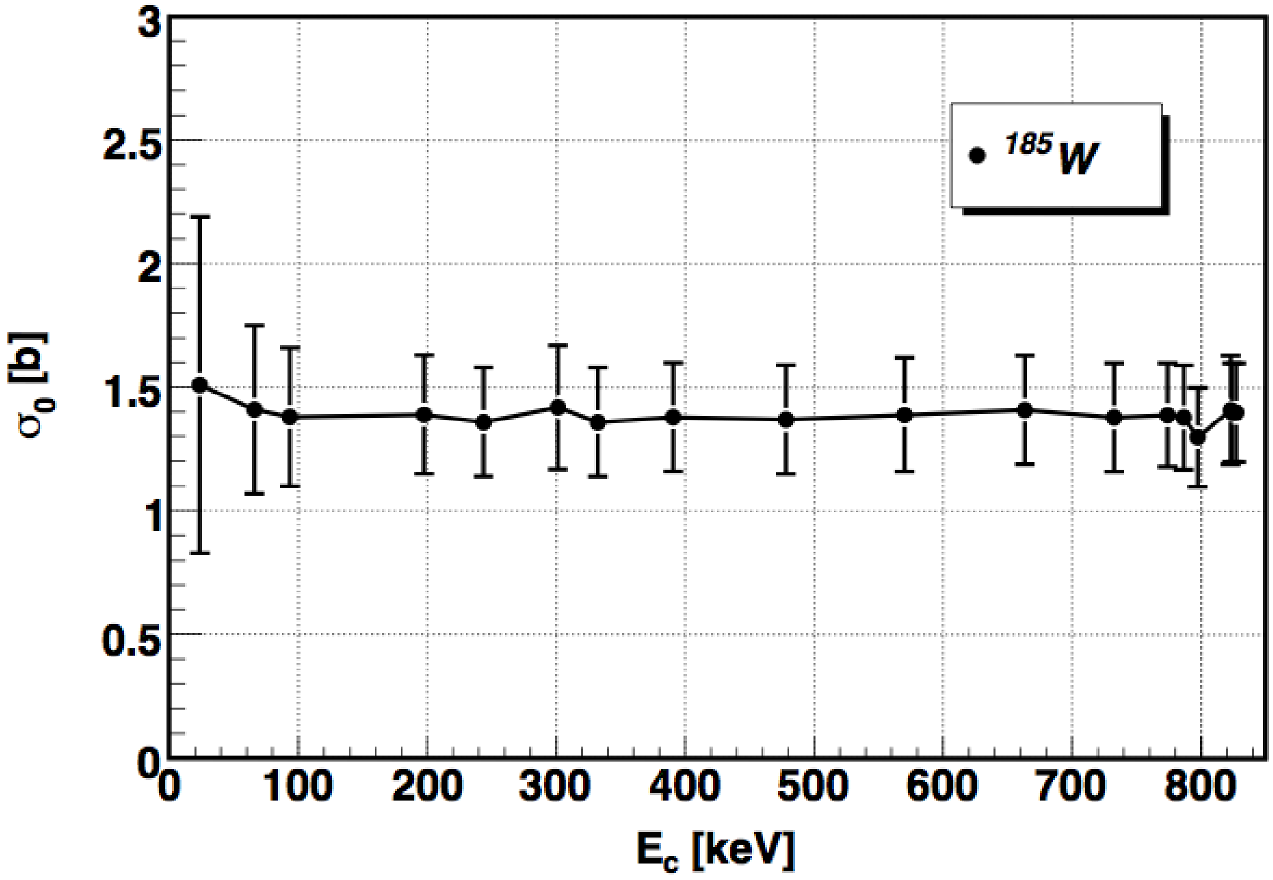
neutron separation energy



$^{A+1}$Aa

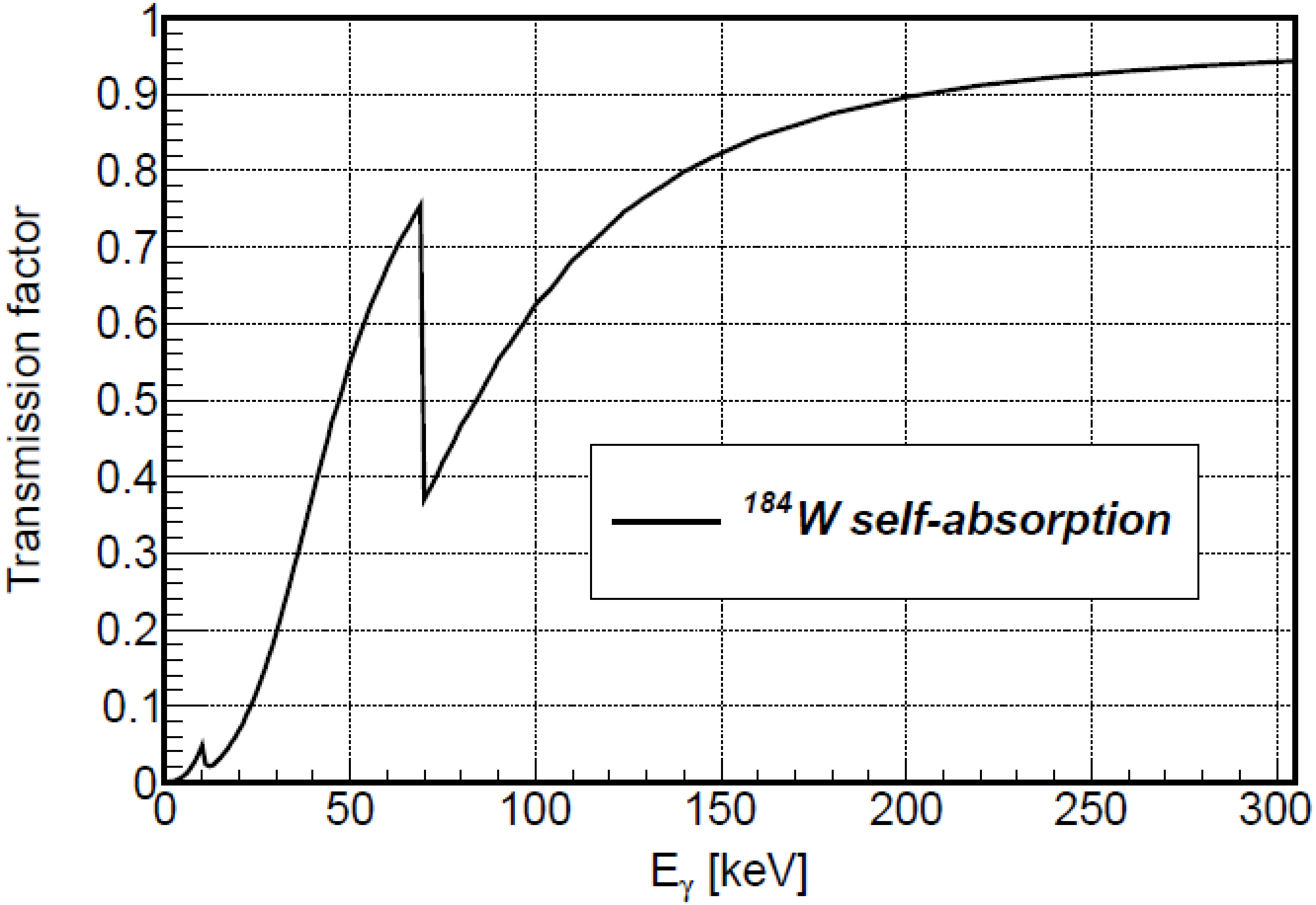
- Compound system formed at high energy
- Neutron separation energy
- Beneath threshold for particle evaporation
- Compound system deexcites through γ-ray emission
- Simulate this process using the Monte Carlo code DICEBOX

σ_0 as a function of E_c

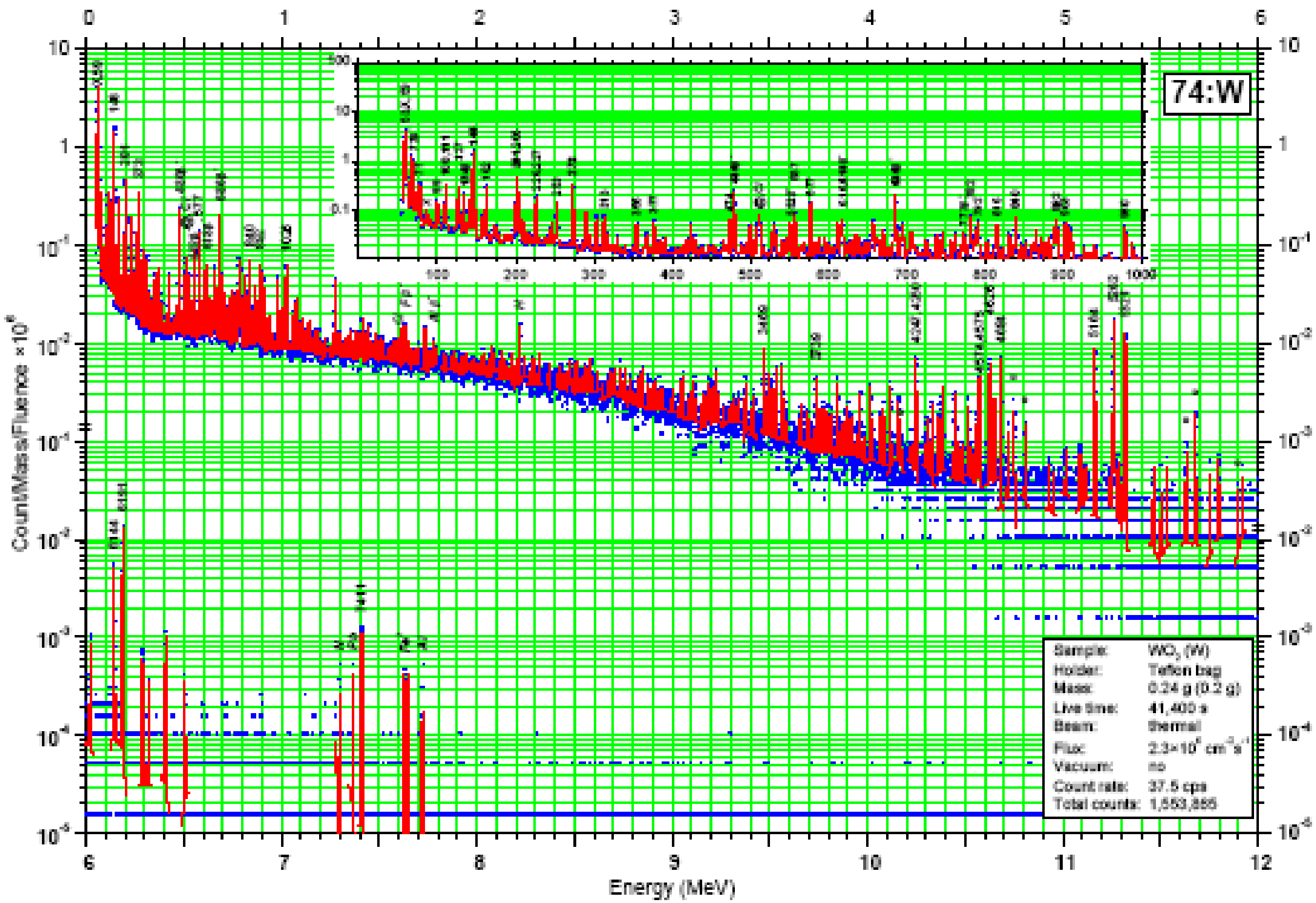


Self-absorption of γ rays in W samples

- sample thickness: 0 – 0.2 mm
- calculation assumes <0.1 mm >



Elemental $_{74}$W capture-γ spectrum



- Na_2WO_6 (s) sodium tungstate calibration
- WO_2 (s) tungsten oxide target

- **^{180}W(n,γ)^{181}W [0.12 %]**
- **^{182}W(n,γ)^{183}W [26.50 %]**
- **^{183}W(n,γ)^{184}W [14.31 %]**
- **^{184}W(n,γ)^{185}W [30.64 %]**
- **^{186}W(n,γ)^{187}W [28.43 %]**

- ENSDF ⇒ γ lines in individual W compound systems
- Separated-W targets: definitive assignments; weaker signatures

Adopted models

Back-shifted Fermi gas (level density) with Von Egidy parameterization

$$\rho(E,J) = f(J)\frac{\exp(2\sqrt{a(E-E_1)})}{12\sqrt{2}\sigma_c a^{1/4}(E-E_1)^{5/4}}$$

[Till von Egidy and Dorel Bucurescu, Phys. Rev. C 72, 044311 (2005)]

Generalized Lorentzian E1 PSF with RIPL parameterization (experimental data)

$$f_{GLO}^{E1}(E_\gamma,\Theta) = \frac{1}{3(\frac{hc}{2})^2}\left[\frac{E_\gamma \Gamma_G(E_\gamma,\Theta)}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2\Gamma_G^2(E_\gamma,\Theta)} + F_K\frac{4\pi^2\Theta^2\Gamma_G}{E_\gamma^5}\right]\sigma_G\Gamma_G$$

Resonance-shape parameters:

E_G (energy centriod), Γ_G (resonance width), σ_G (resonance cross section)

Scissors + spin-flip M1 PSF with parameterization from Yb isotopes

[U. Agvaanluvsan et al., Phys. Rev. C 70, 054611 (2004)]

Isoscalar + Isovector E2 PSF or single particle

DICEBOX: simulation cf. experiment

- DICEBOX calculates theoretical level feedings to all excited states in the input file
- Simulated populations (P_S) can then be compared to measured experimental depopulations (P_E)
- If P_E=P_S $\Rightarrow$ statistical model accurately describes nuclear properties
- Consider hypothetical nucleus ^{XXX}Aa: 4 excited states in rotational sequence; E_{crit}=800 keV
- Critical energy (Ecrit): highest level where all structure information (γ branching, J^{π}) is known
- Increasing transition probability upon descending band as consequence of decay process i.e. a larger γ-decay branch is observed from states with decreasing excitation energy