Challenges in experimental methods/analysis of nuclear level densities

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Neutron resonances

Oslo method

Status of current knowledge of nuclear level density

Experiment

Main experimental basis – neutron resonance spacings from reactions with resonance neutrons
Data bases: RIPL2, RIPL-3, S. Mughabghab compilation.
Other data: Oslo technique, particle evaporation – are not systemized yet and are not used in practical calculations

Models

1. Phenomenological models with free parameters determined from experimental data on **neutron resonances.** These models are used in modern nuclear reaction codes for applications. (Fermi-gas, Gilbert and Cameron)
2. Models based on global microscopical calculations (by S. Goriely)

Possible uncertainties of neutron resonance spacings

- Uncertainties associated with models used to extract level spacings from neutron resonance data

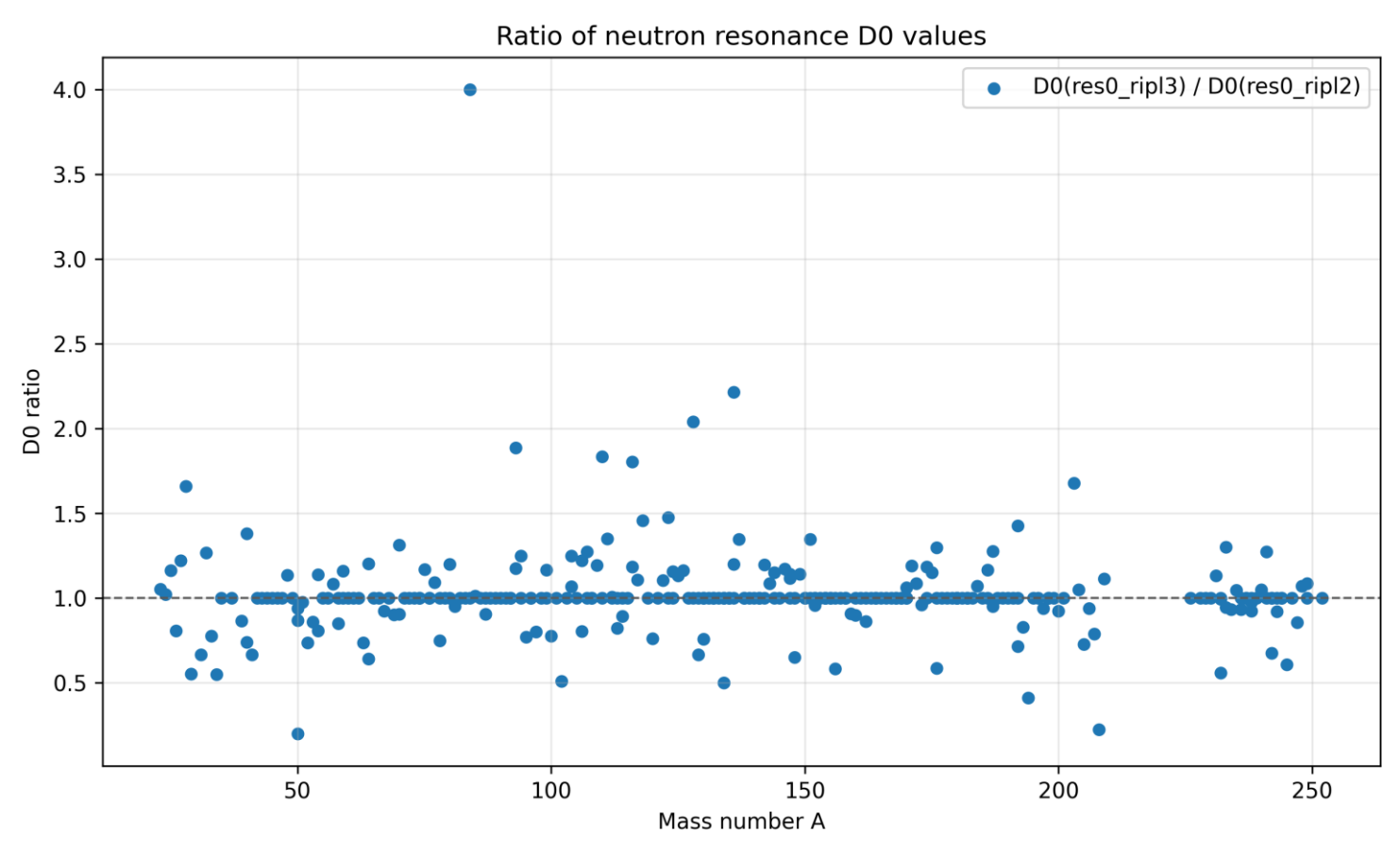
  1. Model used to estimate missing resonances due to experimental threshold (is Porter-Thomas statistics good enough ?)
  2. Model to separate week s-wave resonances from strong p-wave resonances

Lack of documentations of previous evaluations

Different evaluators can produce different D_0, D_1

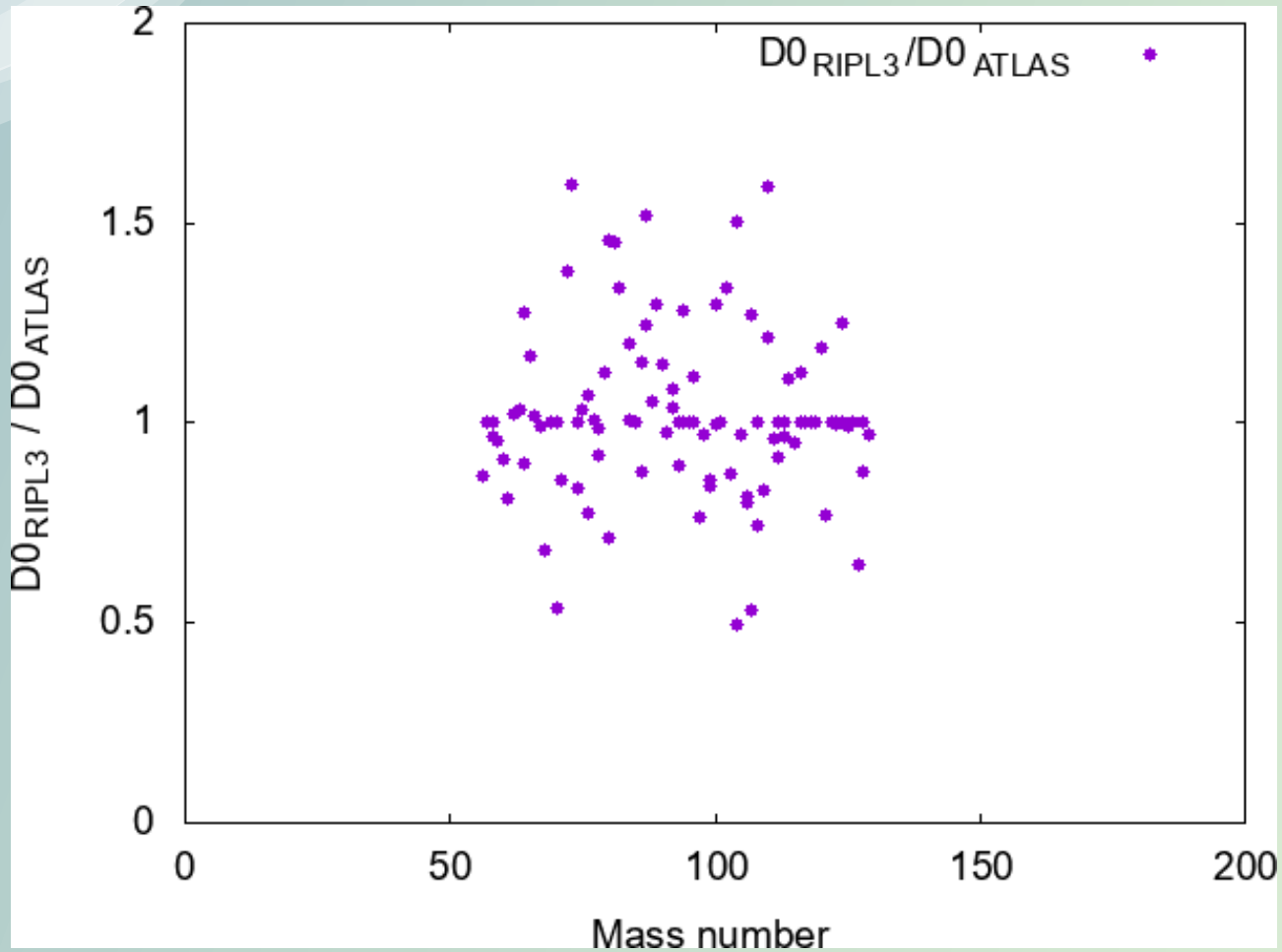
Uncertainty insights from comparing RIPL2 vs RIPL3 data on s-wave resonance spacings (D_0)

RIPL3 vs RIPL 2

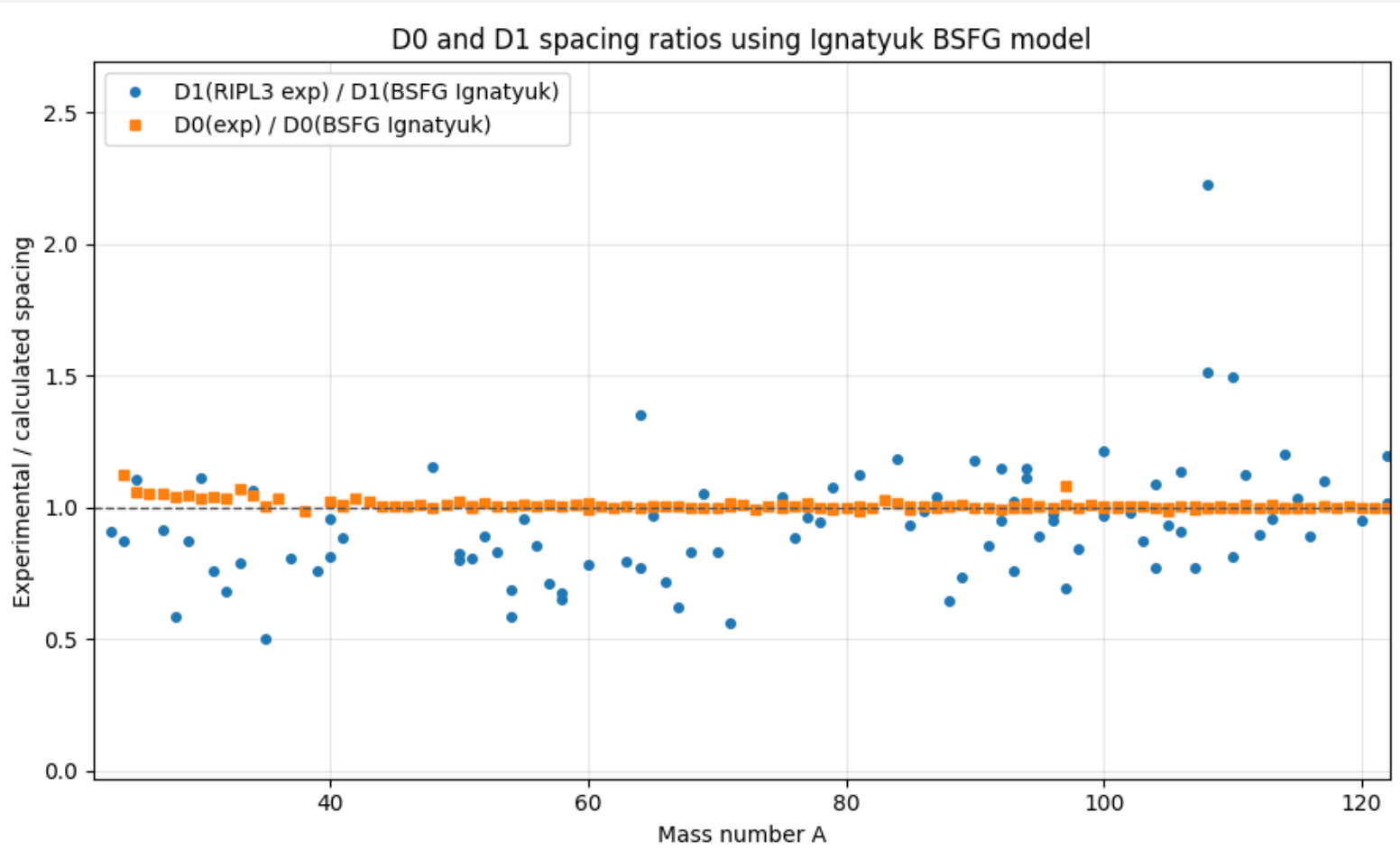


s-wave resonance spacings (D_0)

RIPL3 vs Atlas (S. Mughabghab 2006)



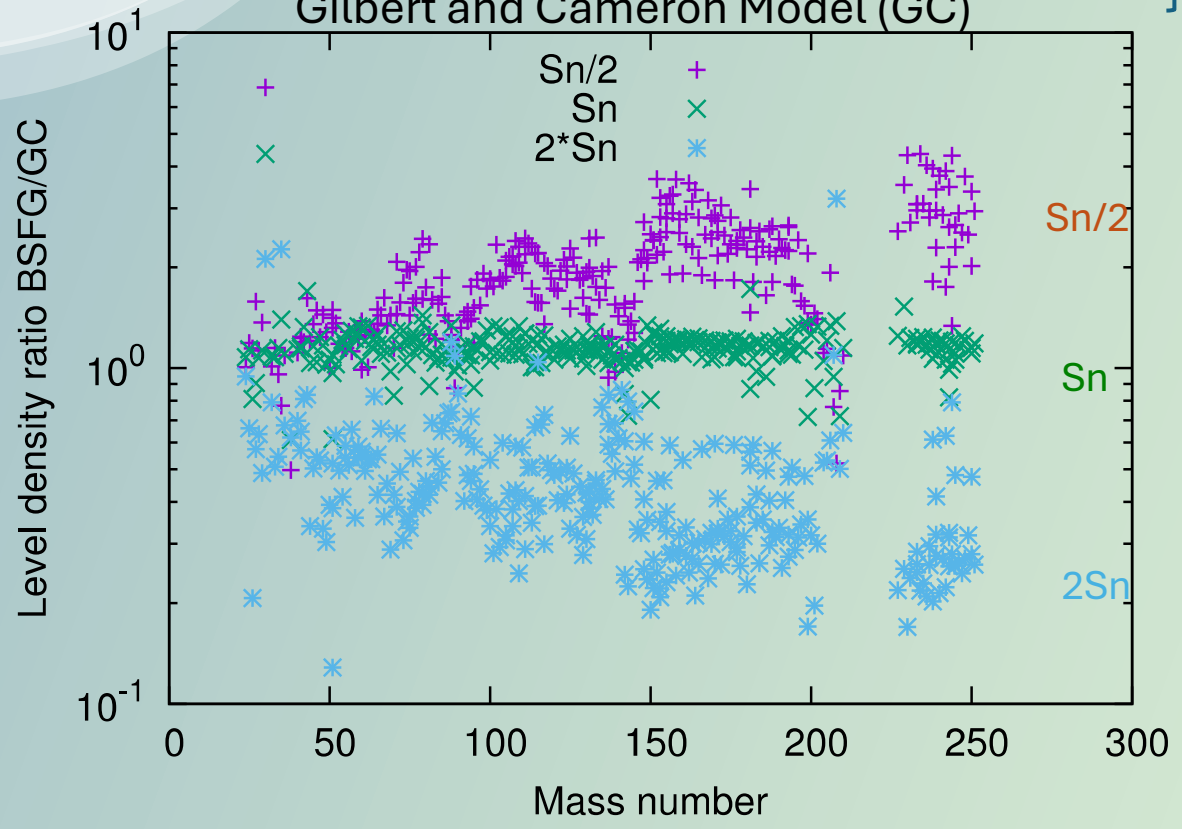
Uncertainty insights from of s-wave (D_0)/p-wave(D_1) resonance spacings



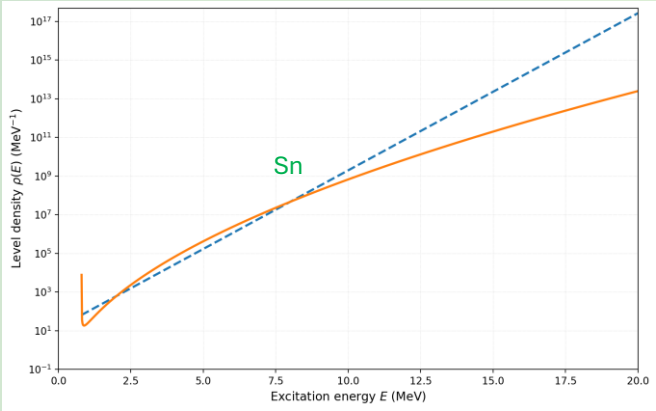
Uncertainties caused by shape of level density function models

Back sh ted Fermi-gas Model (BSFG)
Gilbert and Cameron Model (GC)

parameters from RIPL3



Sn - neutron separation energy



The Oslo method

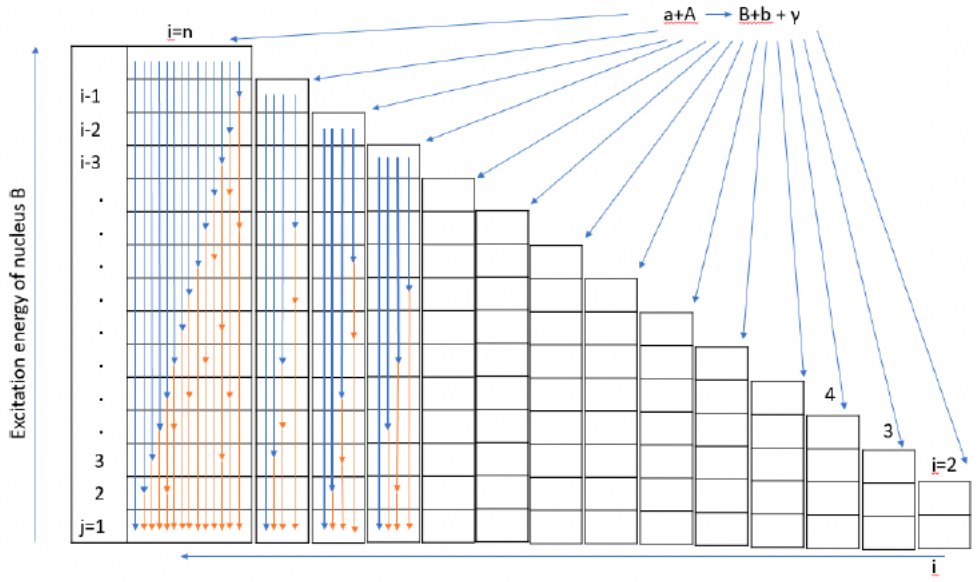


FIG. 1. Schematic representation of γ de-excitation of levels from energy bins E_x^i populated by particles. Each vertical bar represents excitation energy range of the same nucleus populated with different energies of outgoing particles

$$P(E_x, E_\gamma) = \rho(E_x - E_\gamma) \times T(\gamma)$$

Uncertainties related to the spin population in the Oslo method

Traditionally used formula:

$$P(E_x, E_\gamma) = \rho(E_x - E_\gamma) \times T(E_\gamma)$$

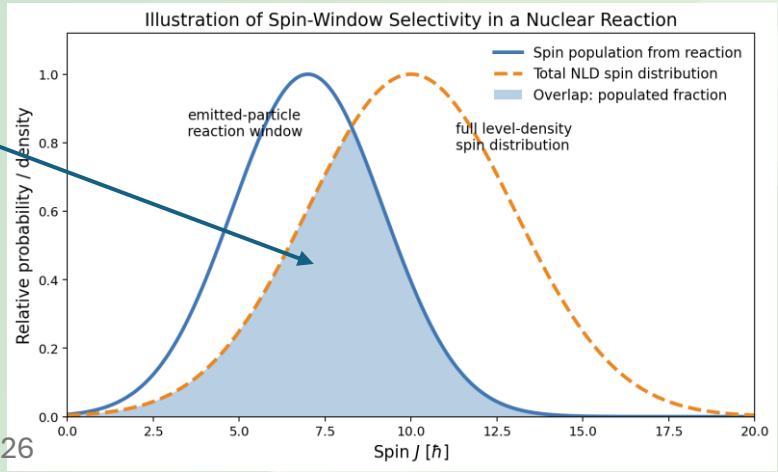
Accurate formula:

$$P(E_x, E_\gamma) = \underbrace{\rho(E_x - E_\gamma) \times K\left(E_x, (E_x - E_\gamma)\right)}_{\rho^{red}(E_x - E(\gamma))} \times T(E_\gamma)$$

$$K(E_x, E^*) = \int_I g_i(E_x, I) \int_{J=I-1}^{J=I+1} g(E^*, J) dJ dI$$

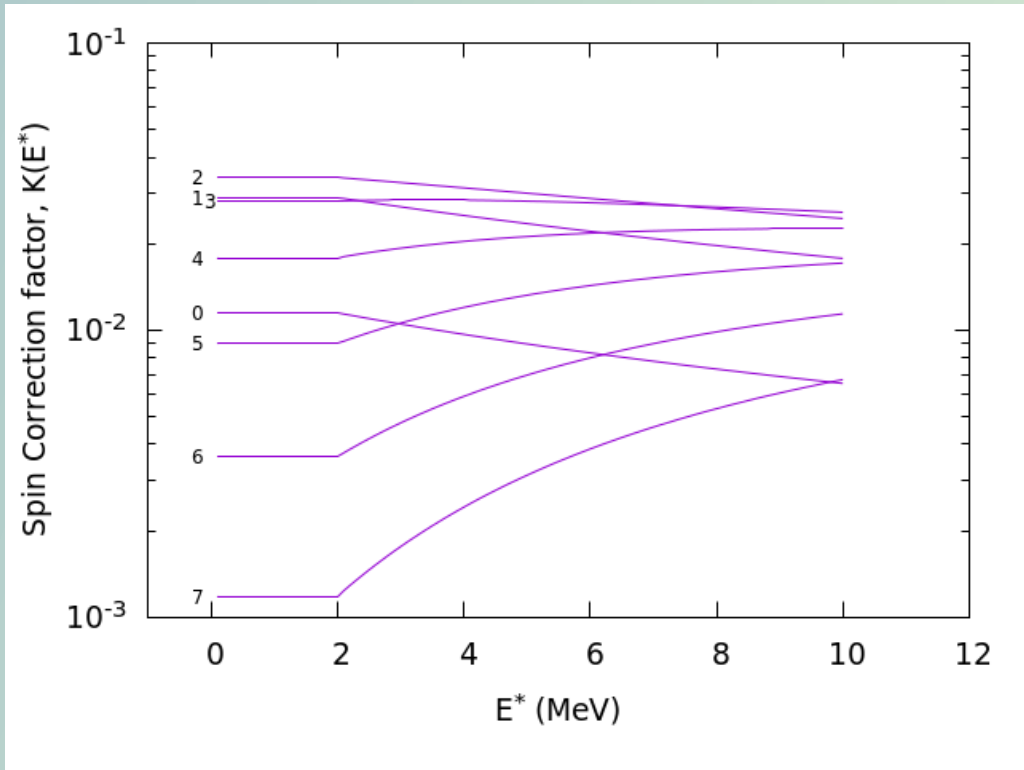
$$g(E^*, J) = \frac{2J+1}{2\sigma^2(E^*)} \exp\left[-\frac{(J+1/2)^2}{2\sigma^2(E^*)}\right]$$

Has a different excitation energy dependence



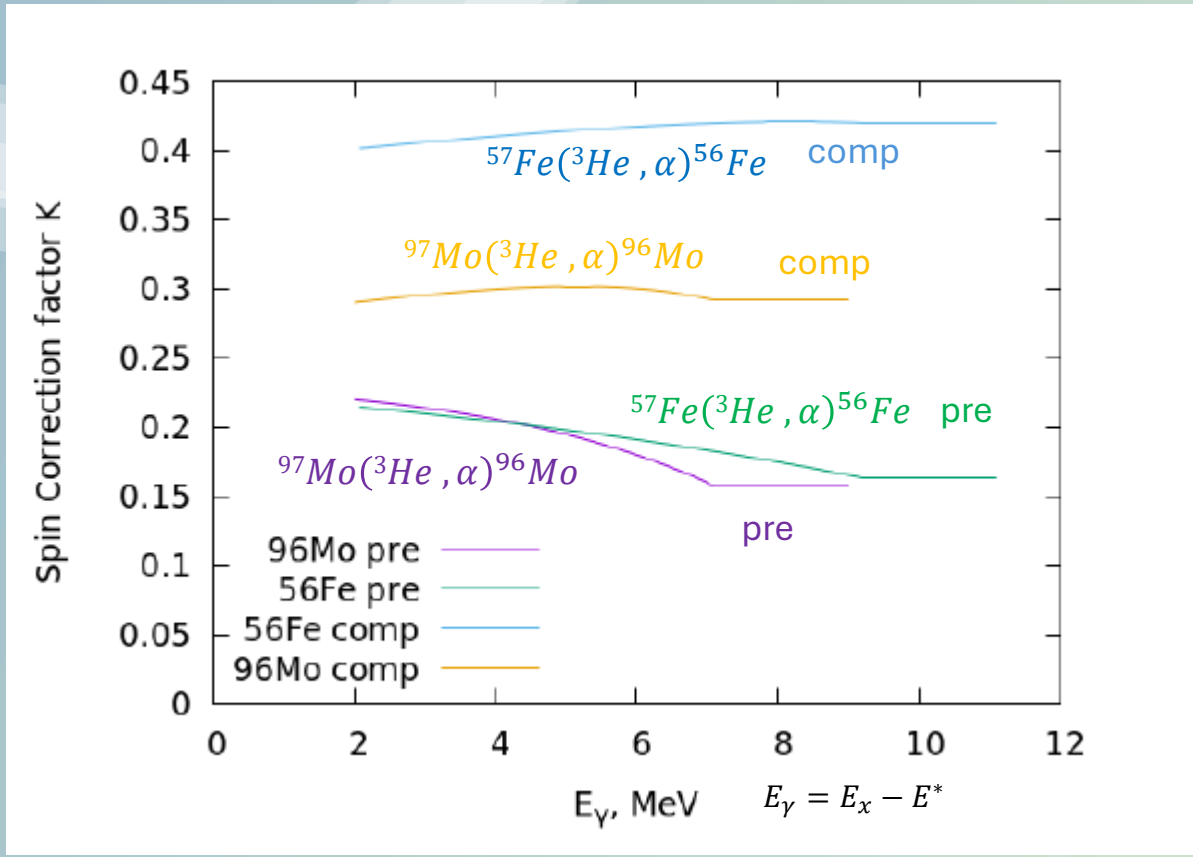
Uncertainties related to the spin population

$$K(E_x, E^*) = \int_{J=I-1}^{J=I+1} g(E^*, J)dJ$$



E_x=const

Uncertainties related to the spin population



Talys

$$K(E_x, E^*) = \int_I g_i(E_x, I) \int_{J=I-1}^{J=I+1} g(E^*, J) dJ dI$$

E_x=const

$$g(E^*, J) = \frac{2J+1}{2\sigma^2(E^*)} \exp\left[-\frac{(J+1/2)^2}{2\sigma^2(E^*)}\right]$$

:1902.02966v2 [nucl-ex] 11 Feb 2019

Impact of restricted spin-ranges in the Oslo Method: The example of (d,p)^{240}Pu

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Abstract. In this paper we present the first systematic analysis of the impact of the populated vs. intrinsic spin distribution on the nuclear level density and γ-ray strength function retrieved through the Oslo Method. We illustrate the effect of the spin distribution on the recently performed ^{239}Pu(d,pγ)^{240}Pu experiment using a 12 MeV deuteron beam performed at the Oslo Cyclotron Lab. In the analysis we couple state-of-the-art calculations for the populated spin-distributions with the Monte-Carlo nuclear decay code RAINIER to compare Oslo Method results to the known input. We find that good knowledge of the populated spin distribution is crucial and show that the populated distribution has a significant impact on the extracted nuclear level density and γ-ray strength function for the ^{239}Pu(d,pγ)^{240}Pu case.

Effect of the spin cutoff parameter on calculation of the total radiative width of neutron resonances

Gamma strength function normalization coefficient:

$$B = \frac{< \Gamma_\gamma >^{exp}}{< \Gamma_\gamma >^{calc}_{B=1}},$$

The total average radiative width of neutron resonances :

$$< \Gamma_\gamma(S_n, I_i, \Pi_i) >= \frac{D_0}{2} \int_{E_\gamma=0}^{S_n} dE_\gamma f(E_\gamma) \cdot E_\gamma^3 \cdot \rho(S_n - E_\gamma) \times \sum_{J=-1}^{J=1} g(S_n - E_\gamma, I_i + J))$$

Most popular spin cutoff parameter model formulas

- Rigid body (RB) model (RIPL, Talys)

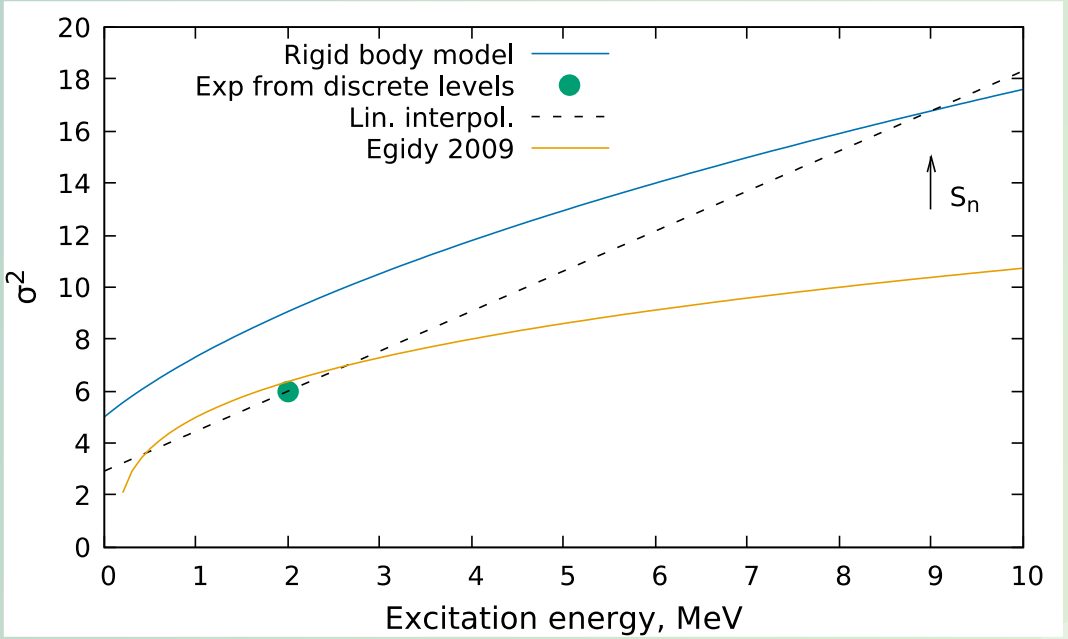
$$\sigma^2(U) = 0.0138 \cdot A^{5/3} \cdot \frac{\sqrt{(U-\Delta)\cdot a}}{\tilde{a}}$$

- T.von Egidy, D. Bucurescu, PRC 80, 054310(2009)

$$\sigma^2(U) = 0.391 A^{0.675}(U - 0.5Pa)^{0.328}$$

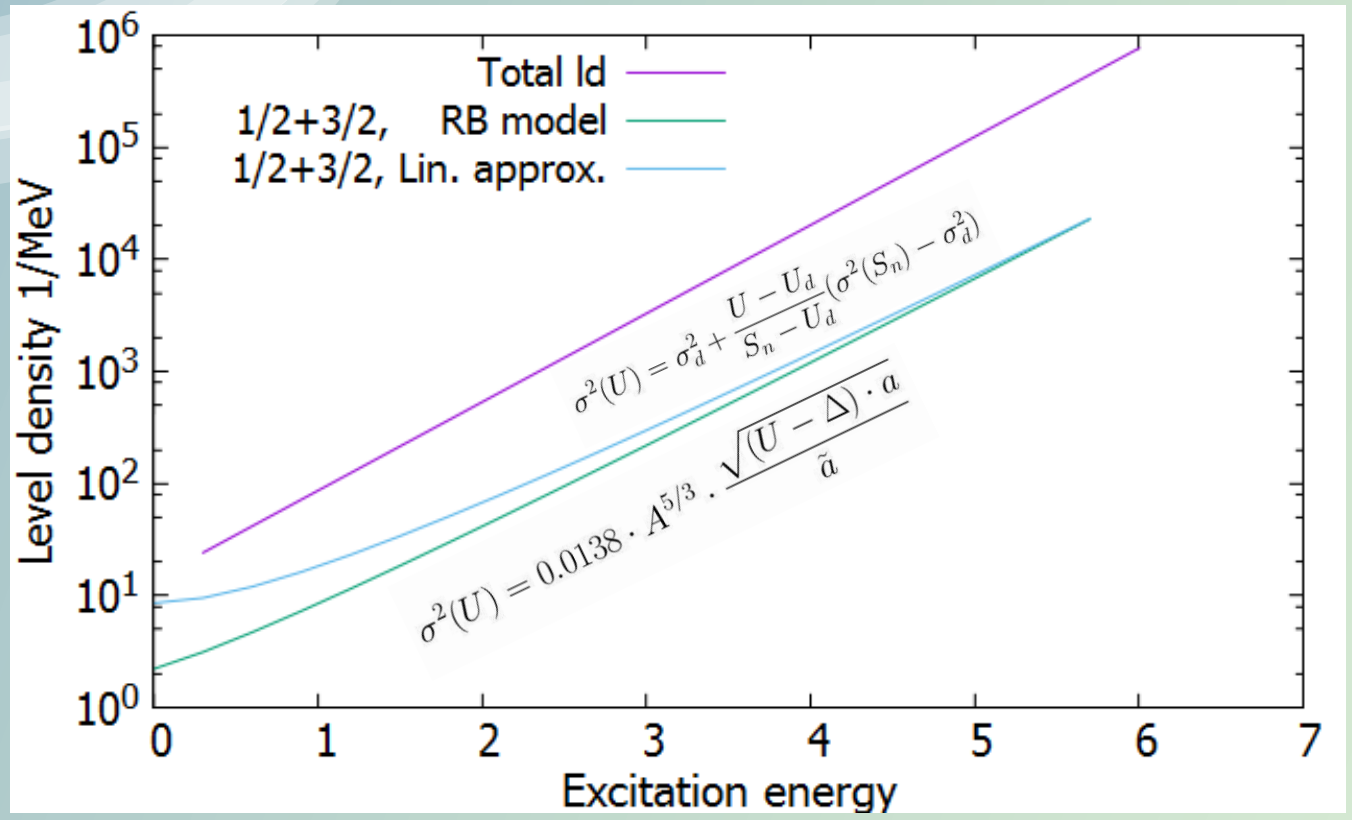
- Linear interpolation between $\sigma(U_d)$ and $\sigma(S_n)$, U_d – average excitation energy for discrete levels (Talys, Empire)

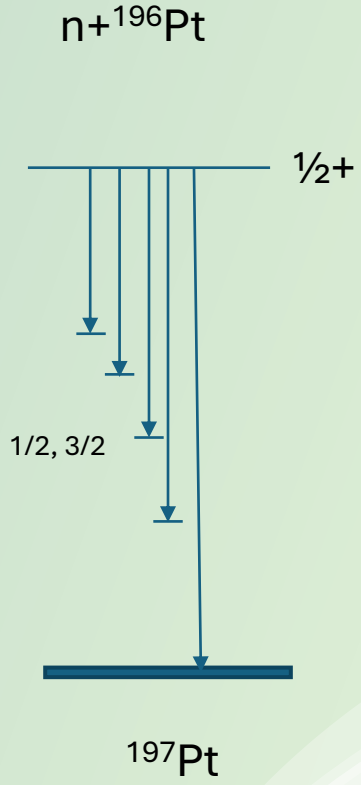
$$\sigma^2(U) = \sigma^2(U_d) + \frac{U - U_d}{S_n - U_d}(\sigma^2(S_n) - \sigma(U_d))$$



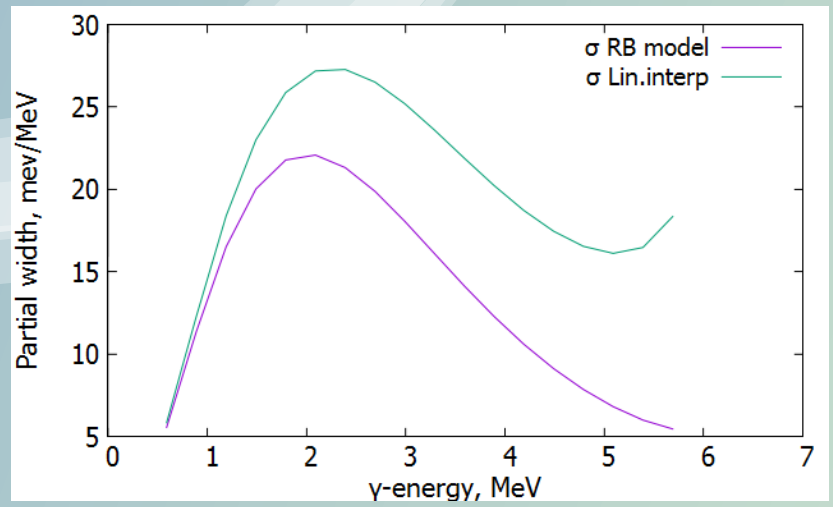
Effect of the spin cutoff on $<\Gamma_\gamma>$, the case of ^{197}Pt

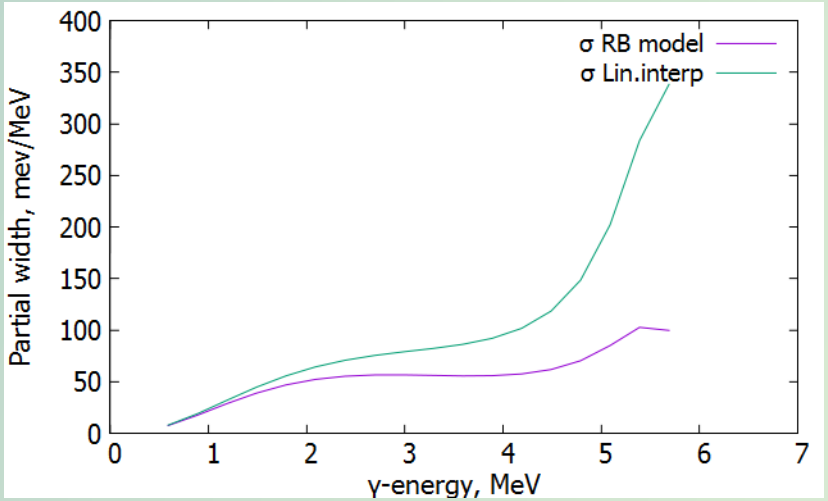
Model level density for ^{197}Pt





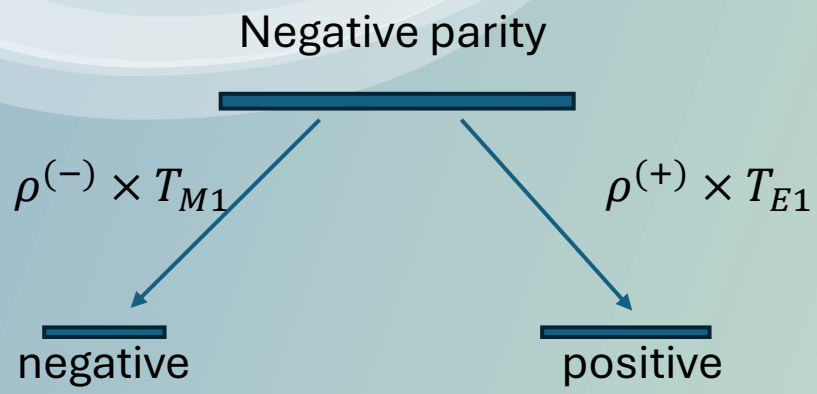
Effect of the spin cutoff on $\langle\Gamma_\gamma\rangle$, the case of ^{197}Pt





Average	total $\langle\Gamma_\gamma\rangle$	of neutron	resonances
	RB model	Lin. Interp.	Ratio
$\langle\Gamma_\gamma\rangle$ no pygmy	78	113	1.45
$\langle\Gamma_\gamma\rangle$ pygmy	382	656	1.71

Uncertainties related to parity populations in the Oslo method



$$\rho^{+} = \rho^{-} \qquad P(E_\gamma) \propto \rho^{(-)} \times T_{M1} + \rho^{(+)} \times T_{E1} = 0.5\rho \times (T_{M1} + T_{E1})$$

$$\rho^{+} \neq \rho^{-} \qquad P(E_\gamma) \propto \rho^{-} \times T_{M1} + \rho^{(+)} \times T_{E1} \neq 0.5\rho \times (T_{M1} + T_{E1})$$

Uncertainties related to parity populations in the Oslo method

$\rho_i^- = \rho_i^+;\ \rho_f^- = \rho_f^+$	$\rho_i^- = \rho_i^+;\ \rho_f^- \neq \rho_f^+$	$\rho_i^- \neq \rho_i^+;\ \rho_f^- = \rho_f^+$	$\rho_i^- \neq \rho_i^+;\ \rho_f^- \neq \rho_f^+$
$P = \rho \times T$	$P = \rho \times T$	$P = \rho \times T$	$P \neq \rho \times T$

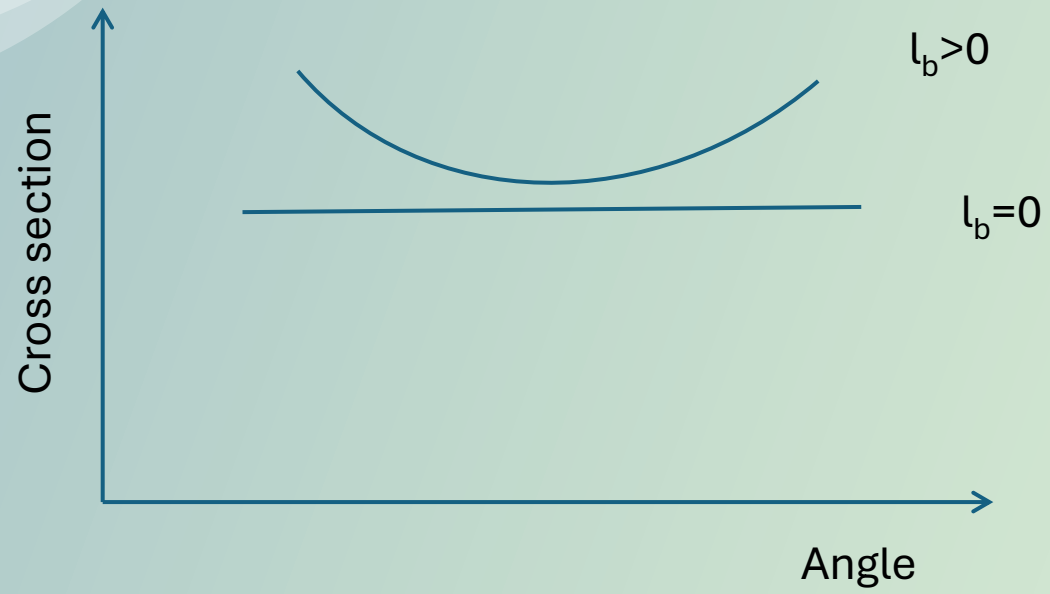
When the numbers of negative- and positive-parity levels are not equal for both the initial and final states, the disentanglement of the primary spectrum into a product of the level density and the gamma-strength function is not possible.

Spin cutoff σ from angular distribution of particles from compound nuclear reactions

T.Ericson and V. Strutinski, Nucl.Phys. 8, 284 (1958)

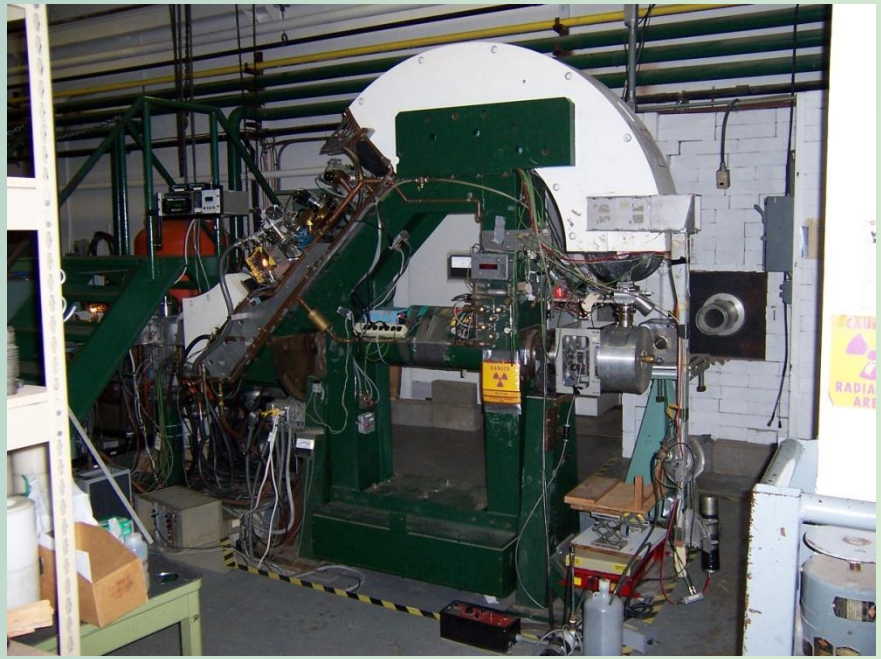
- Due to orbital momentum conservation, spin of compound nuclei tend to be aligned with orbital momentum of incoming particles
- Compound nucleus “remembers ” direction of incoming beam.
- Angular distributions become non-isotropic but symmetric about 90 degree in the center of mass system
- Degree of anisotropy is determined by the angular momenta of outgoing particles which are mainly determined by the spin distribution of residual nucleus

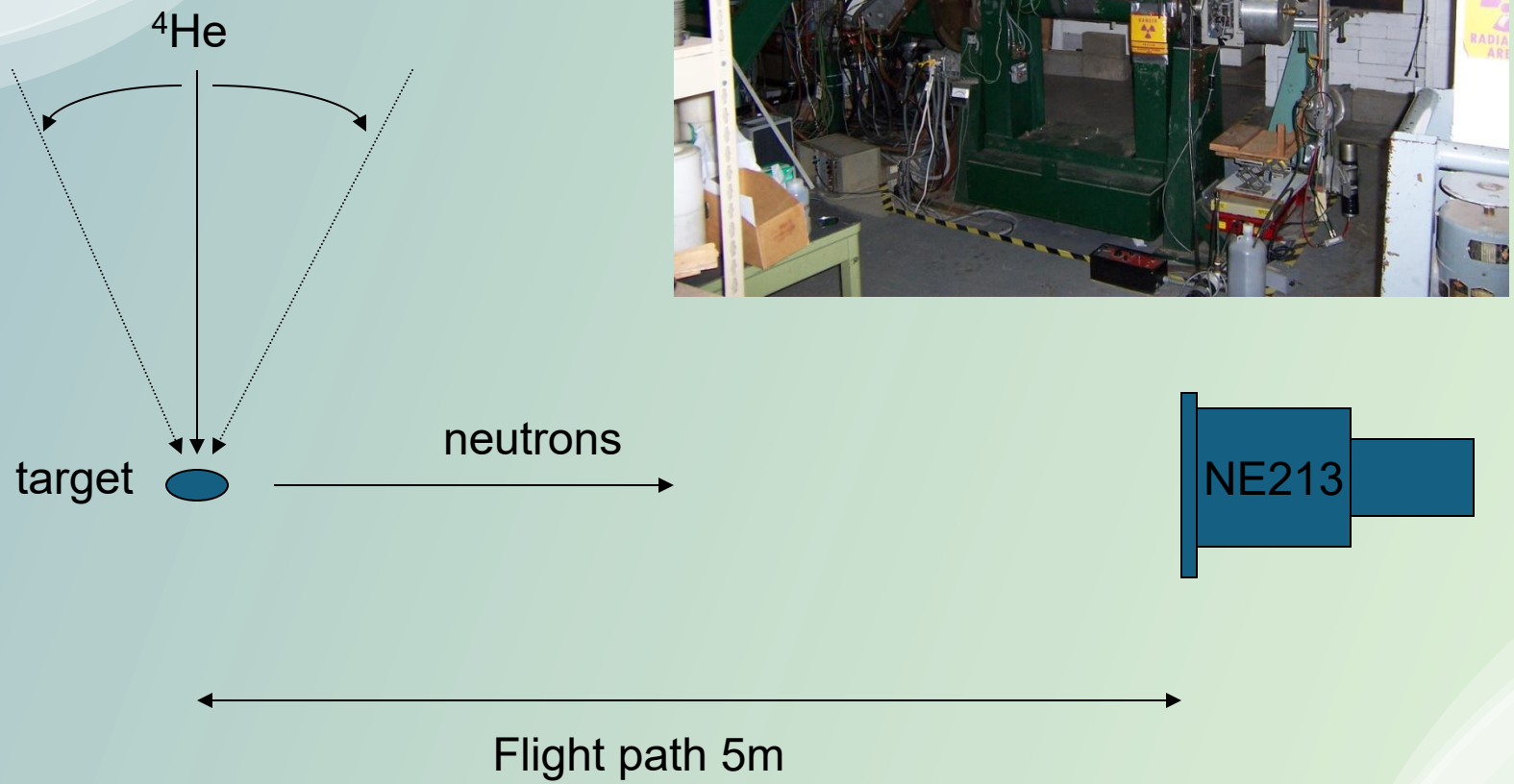




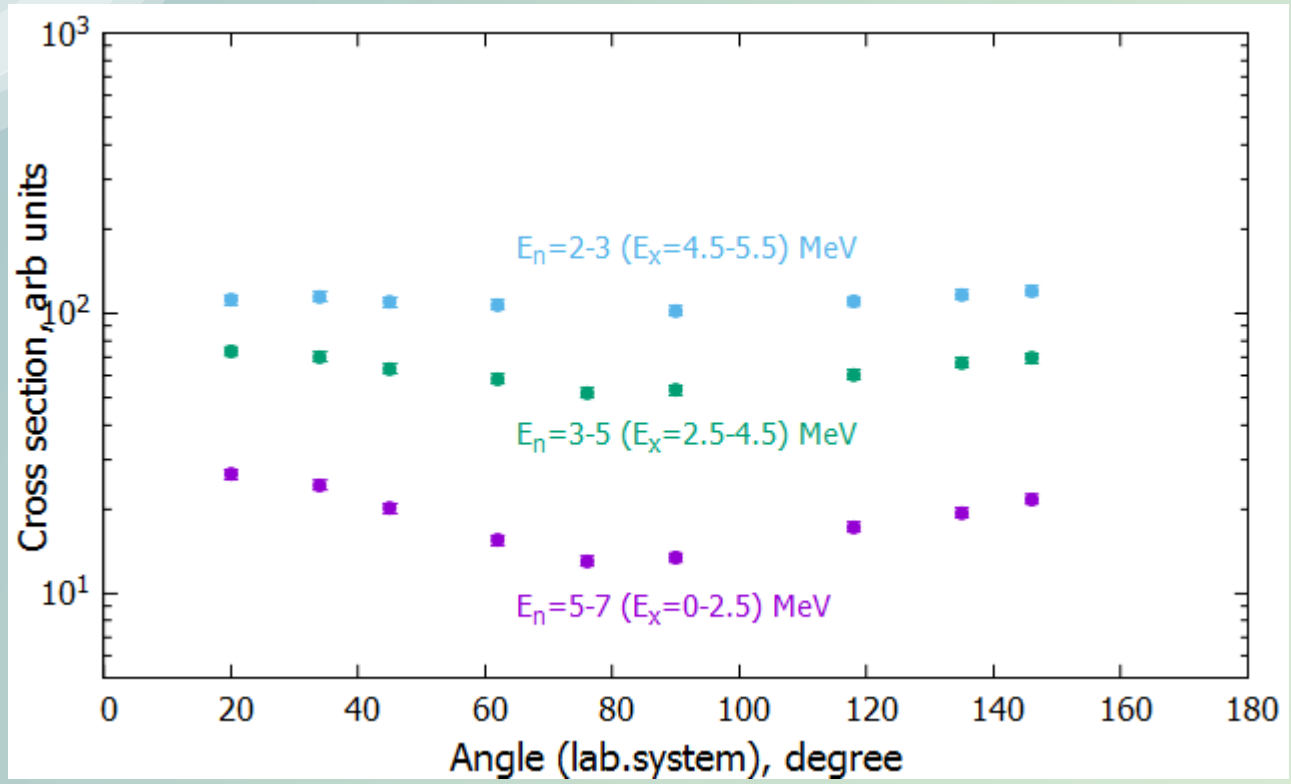
Orbital momenta are determined by spin of both compound C and residual nucleus B

Neutron angular distributions from $^{57}Fe(a,n)^{60}Ni$ reactions, 13.5 MeV beam



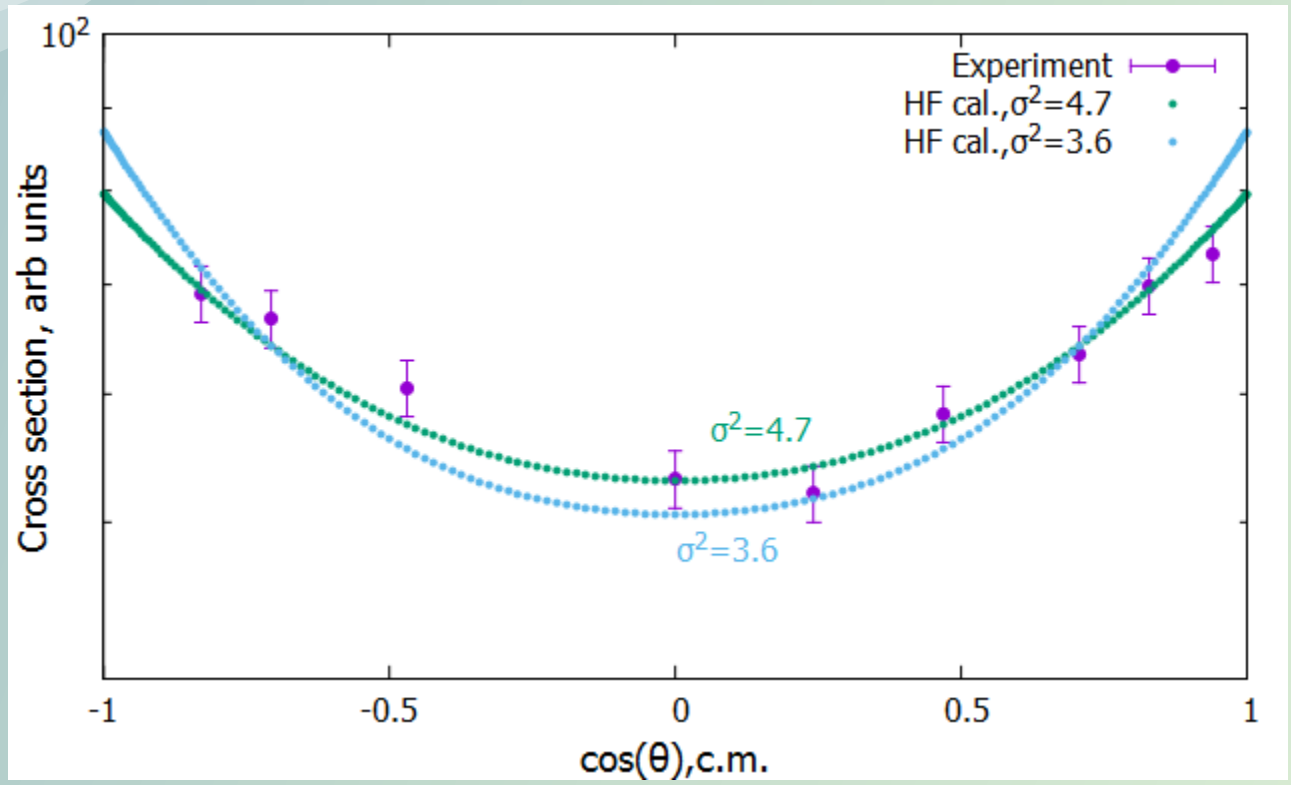


Experimental angular distributions of neutrons from $^{56}Fe(\alpha,n)^{59}Ni$, $E_\alpha = 13.5$ MeV



A.V. Voinov et al, Phys.Rev. C 108, 034302 (2023)

Experimental neutron angular distributions have been analyzed with Hauser Feshbach code developed at Ohio University (S. Grimes).
The spin cutoff parameter has been adjusted to reproduce experimental angular distributions.



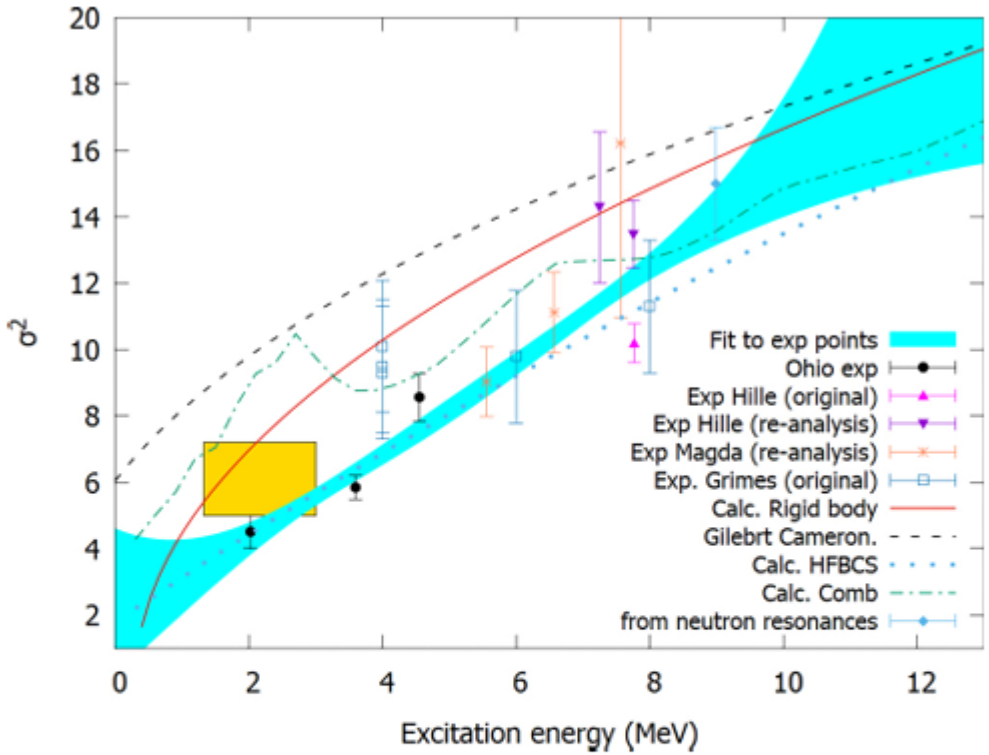


FIG. 5. Points are experimental values of the spin cutoff parameter derived from angular distributions, discrete level scheme, and neutron resonances. Lines are model calculations. The fit to all experimental data points and its uncertainty are shown by the shaded area. The shaded box at around 2 MeV shows the spin cutoff value derived from a discrete level scheme.

A.V. Voinov et al, Phys.Rev. C 108, 034302 (2023)

- Below the neutron separation energy, the spin cutoff parameter tends to be lower than estimations based on RB model.

S. M. Grimes, J. D. Anderson, J. W. McClure, B. A. Pohl, and C. Wong, Level density and spin cutoff parameters from continuum (p, n) and (α, n) spectra, Phys. Rev. C **10**, 2373 (1974).

M. T. Magda, A. Alevra, I. R. Lukas, D. Plostinaru, E. Trutia, and M. Molea, Statistical emission and nuclear level densities in (α, n) reactions, Nucl. Phys. A **140**, 23 (1970).

P. Hille, P. Speer, M. Hille, K. Rudolph, W. Assmann, and D. Evers, Spin dependence of the nuclear level density from angular distributions of (α, n) reactions, Nucl. Phys. A **232**, 157 (1974).

Conclusion on uncertainty issues

Neutron resonance spacing values might include uncertainties related to analysis and/or model assumptions. Efforts on re-evaluations of resonance data are ongoing at IAEA and NNDC.

Data analysis of the Oslo type of experiments should account for the spin distribution and its energy dependence below the neutron separation energy. There might be correction factors to the traditional Oslo type of analysis. Potential problem of unequal negative and positive parity should be assessed on case-by-case basis.

Since spin/parity issues is important, experimental techniques should be developed to target this problem. One possible direction is measuring angular distribution of emitted particles from compound reactions.