Milan Krtička

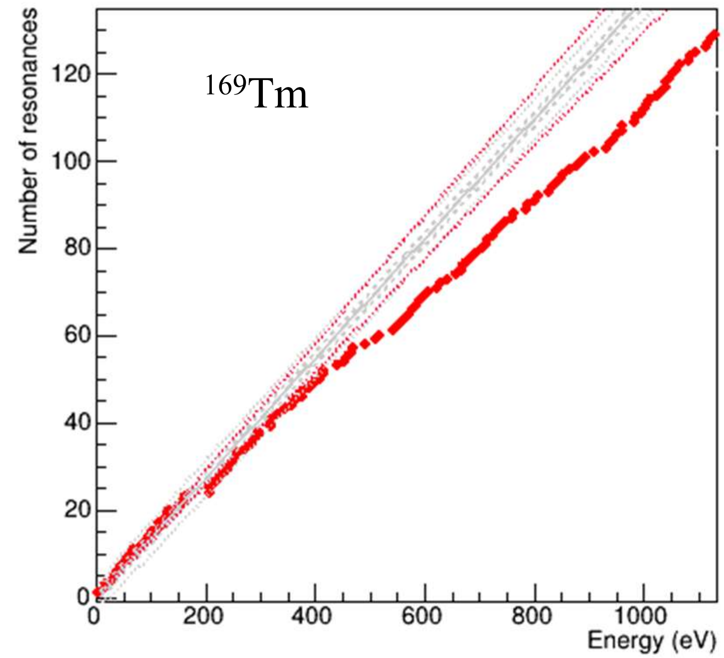
Average spacing
(+ total radiative widths) of neutron resonances
(+ neutron strength functions)

1st NLD CRP Meeting, March 24-28, 2025

Introduction

- Average resonance spacing and total radiative widths (and neutron strength functions) derived from experimental data are key quantities used in many nuclear physics applications, including testing of level density models and normalization of many experiments.

- The spacing is typically **not given by the number observed resonances** within an interval, see below



- Resonance parameters typically measured several times for each isotope (in transmission, capture, fission if relevant, …)
- Authors often tried to determine the average resonance parameters (D_0, Γ_γ, S_l) from the measurement – several different approaches typically adopted, some of them should be taken with caution (fitting of cumulative distribution…)

- Several "large" compilations prepared in the past

Introduction

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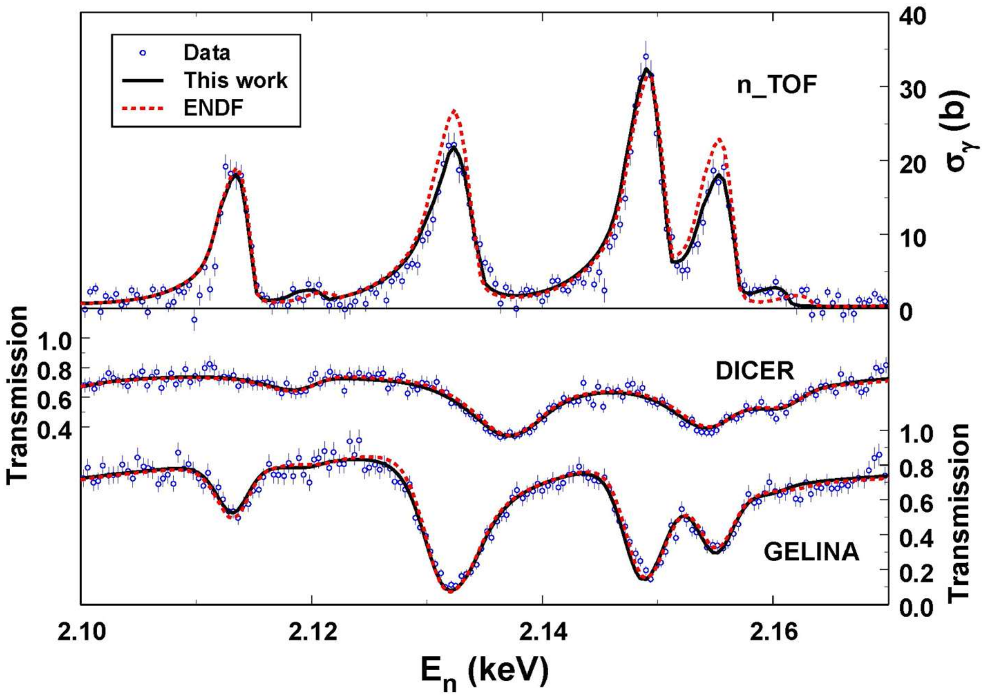
- Available compilations:
  - Atlas of resonances from Said Mughabghab (several editions, last from 2018) – primary source of information for the community measuring neutron-induced reactions (resonances) ☺ (individual resonances are provided)
  - RIPL-based compilations, RIPL-3 (2009) the most recent – usually primary source of information for others ☺
  - Different libraries (ENDF, JEFF, JENDL, …) adopt various values
  - The way how compilations made is largely **undocumented**
    (meaning of uncertainties, how values determined, …)

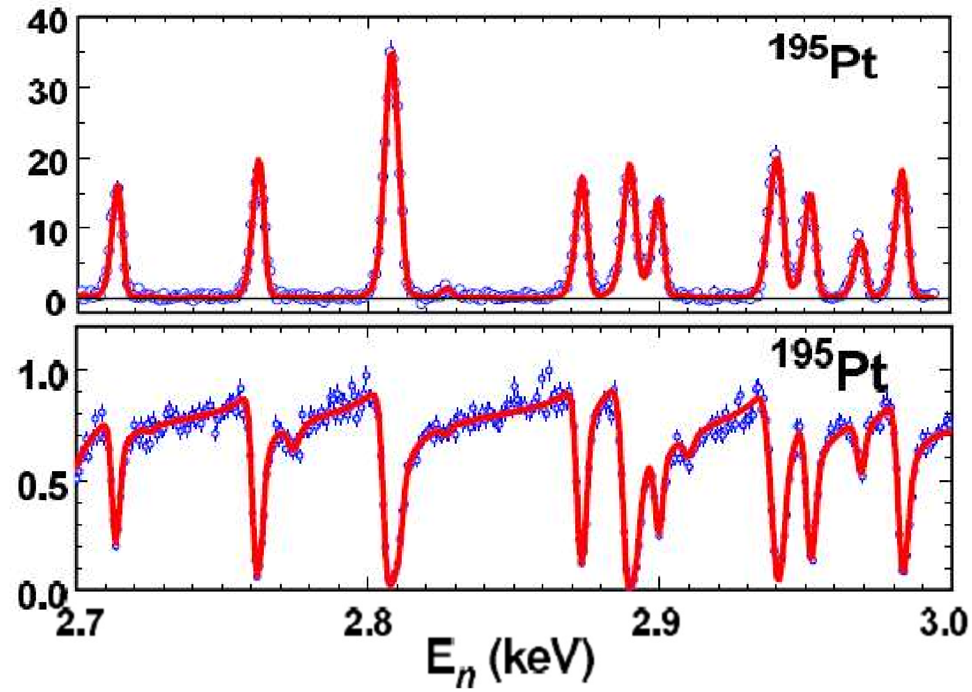
- The consultants meeting for this CRP recommended updating this database
  (should by probably responsibility of MK☺).

Example of TOF spectra

- Transmission and capture (+ fission) data measured for all stable targets (isotopes) (only elemental data in some cases)
- Some data available also for unstable nuclei (with lifetime larger than about a year)



P.E. Koehler at al., Eur. Phys. J. A (2022) 58:195

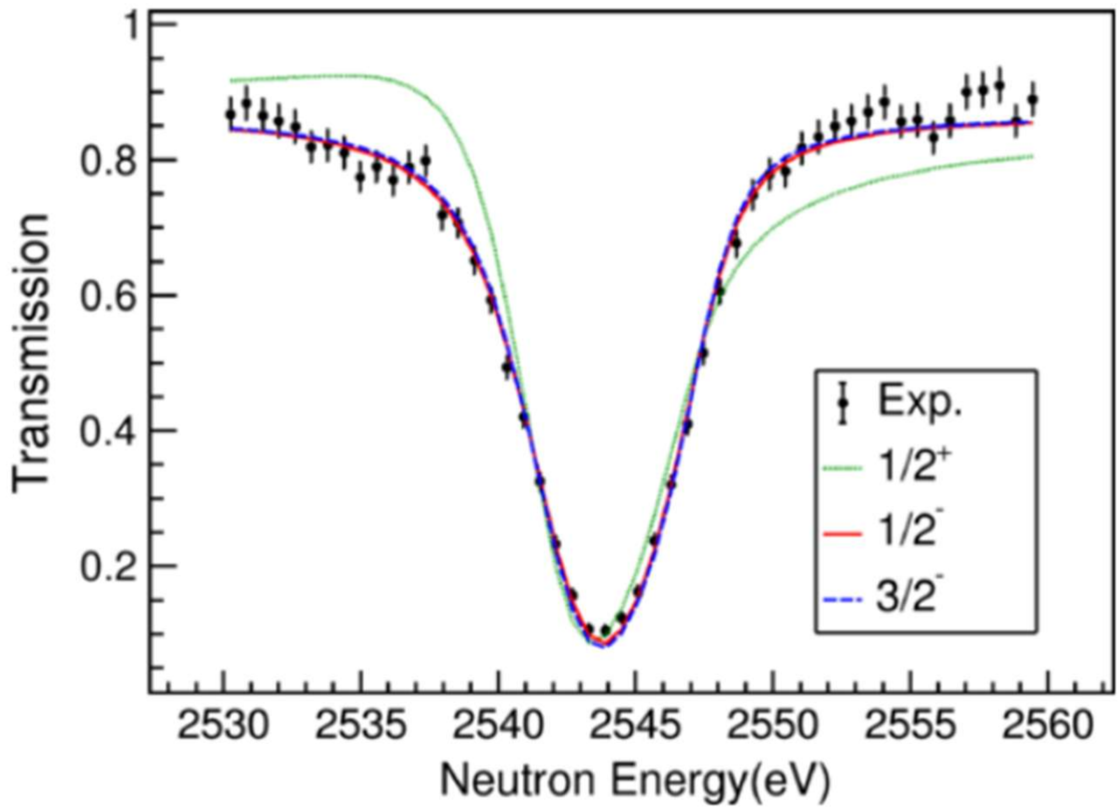


ORELA data, P.E. Koehler … unpublished

Observed data - Resolution function

Resonance in ^{140}Ce (GELINA)

Transmission



$E = 2.543$ keV
$\Gamma_n = 425.7(4.4)$ meV
$\Gamma_\gamma = 59.63(0.36)$ meV
$\Gamma \approx 0.485$ eV

Observed width

- More than an order of magnitude larger than the actual width – direct determination of Γ from observed width extremely difficult
- Depends on facility

$$\sigma = \pi \lambda_n^2 \frac{g\Gamma_n\Gamma_{\mathrm{out}}}{(E - E_R)^2 + \Gamma^2/4}$$

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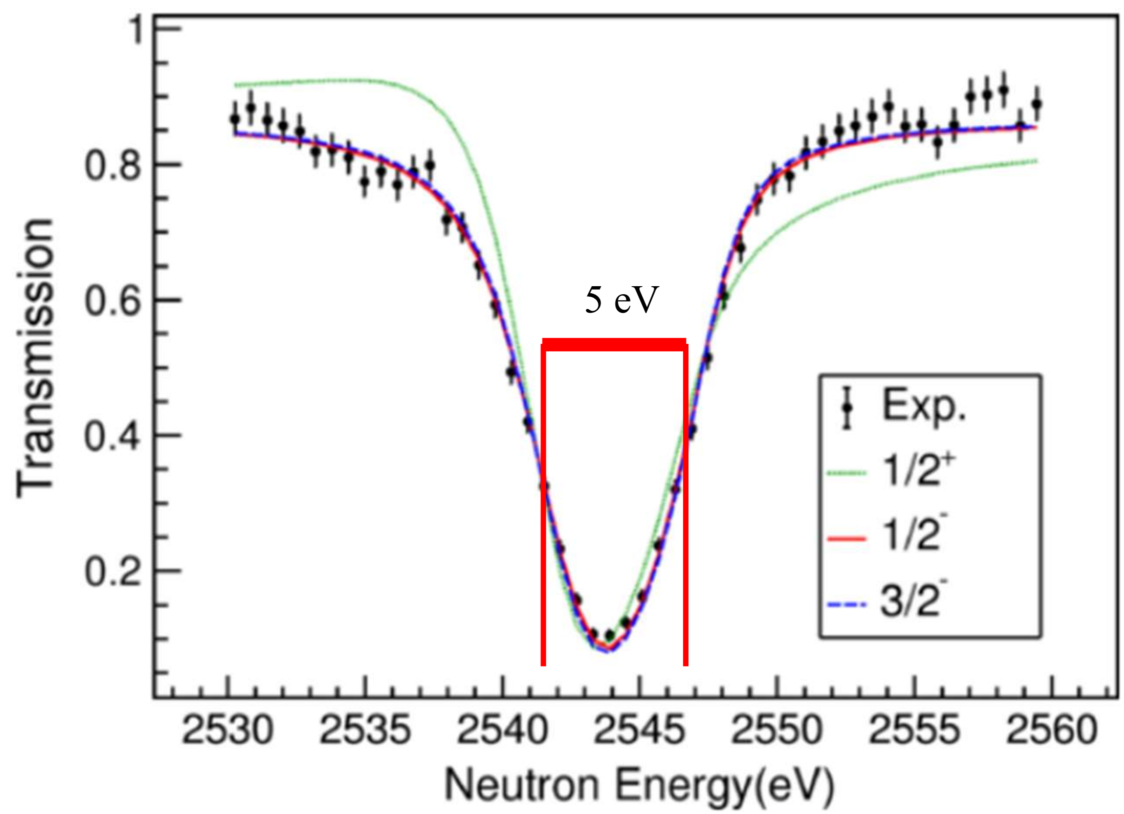

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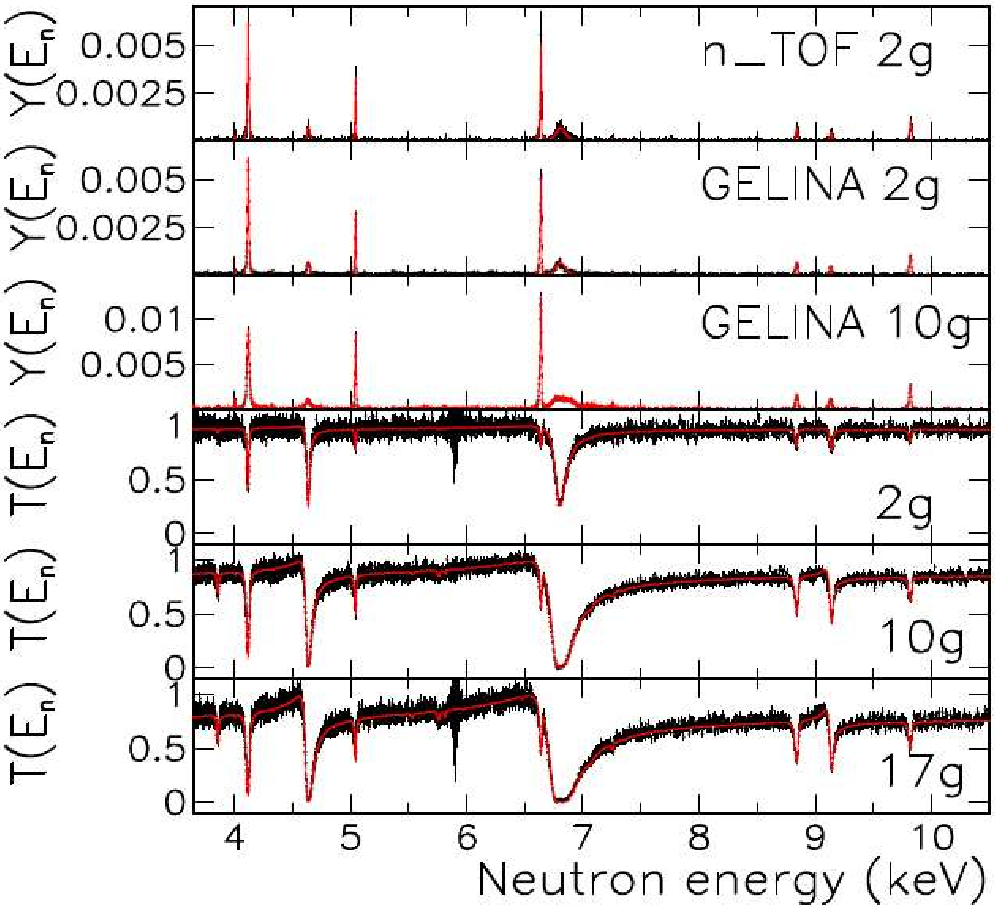
Deduced resonance parameters



- The measured data is (typically) fitted with codes that take into account "broadening effects"
  - Facility resolution function,
  - Doppler broadening,
  - multiple interactions in the sample)

- Several codes available (SAMMY, REFIT, …)
- Resonance parameters "derived" (E, Γ_n, Γ_γ, J, π) … not always all

G. Tagliente et al. (n_TOF coll.), PRC **105**, 025805 (2022)

Deduced resonance parameters

The analysis codes can usually produce reliable information on the "resonance area"

- Capture kernels $k = g\Gamma_n \Gamma_\gamma / \Gamma$, $\Gamma = \Gamma_n + \Gamma_\gamma$ (from capture data)
  k dominated by smaller of the widths
- "Neutron strengths" $g\Gamma_n$ (from transmission data)

- In favorable cases also additional information (on g)

(Γ_n - neutron decay width)
(Γ_r, often Γ_γ – reaction (γ) decay width)

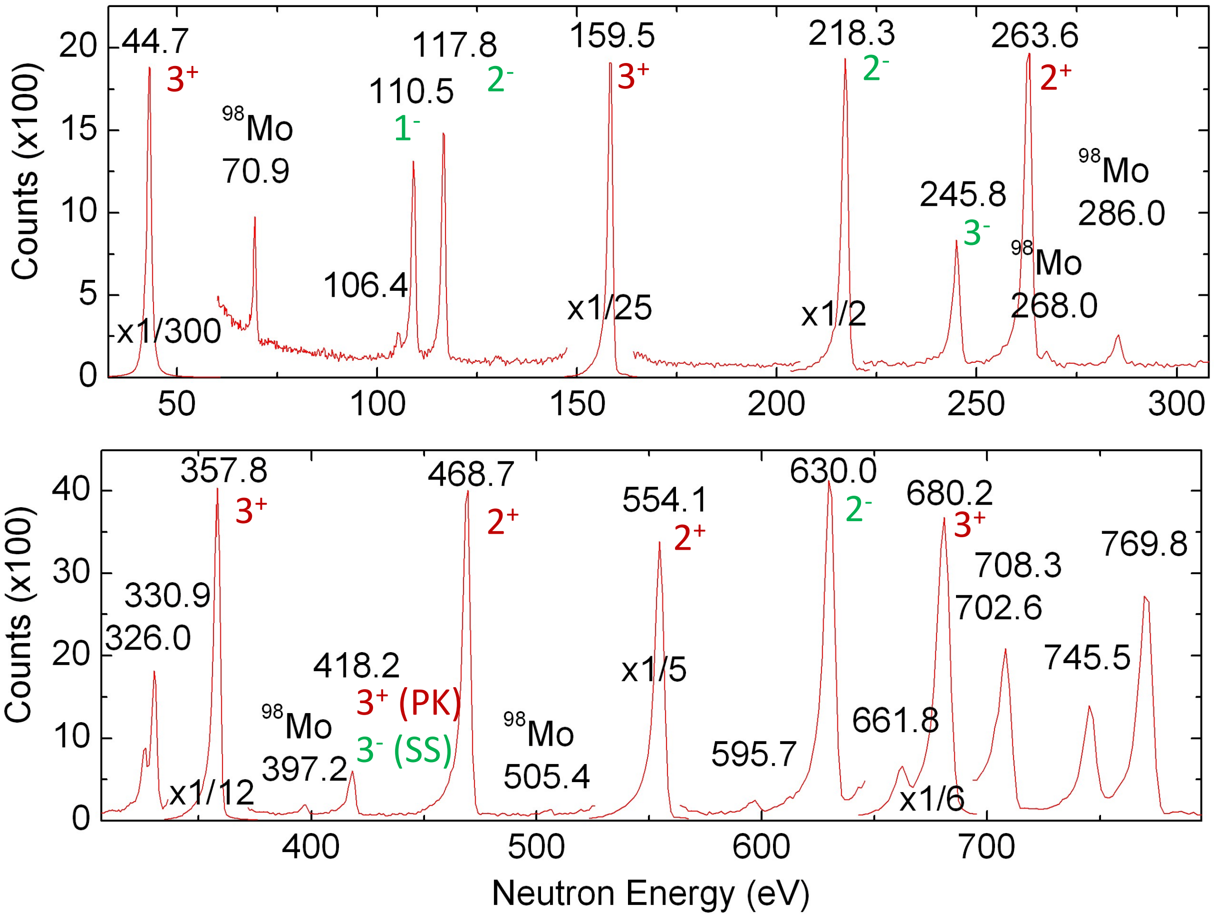
$$\sigma = \pi \lambda_n^2 \frac{g\Gamma_n \Gamma_{\text{out}}}{(E - E_R)^2 + \Gamma^2/4}$$

In limiting cases:

Areas A are given by:	$\Gamma_r \ll \Gamma_n$	$\Gamma_r \gg \Gamma_n$
Reaction (capture "r=γ"):		
$A_{r,\text{thin}} \propto n\, g \frac{\Gamma_n \Gamma_r}{\Gamma}$	$n\, g\, \Gamma_r$	$n\, g\, \Gamma_n$
Transmission:		
$A_{t,\text{thin}} \propto n\, g\, \Gamma_n$	$n\, g\, \Gamma_n$	$n\, g\, \Gamma_n$
$A_{t,\text{thick}} \propto \sqrt{n\, g\, \Gamma_n\, \Gamma}$	$\sqrt{n\, g}\, \Gamma_n$	$\sqrt{n\, g\, \Gamma_n\, \Gamma_r}$
Deducible parameters:	g, Γ_n, Γ_r	g, Γ_n

& Γ if comparable to / larger than Δ_R and Δ_D (resolution and Doppler broadening)

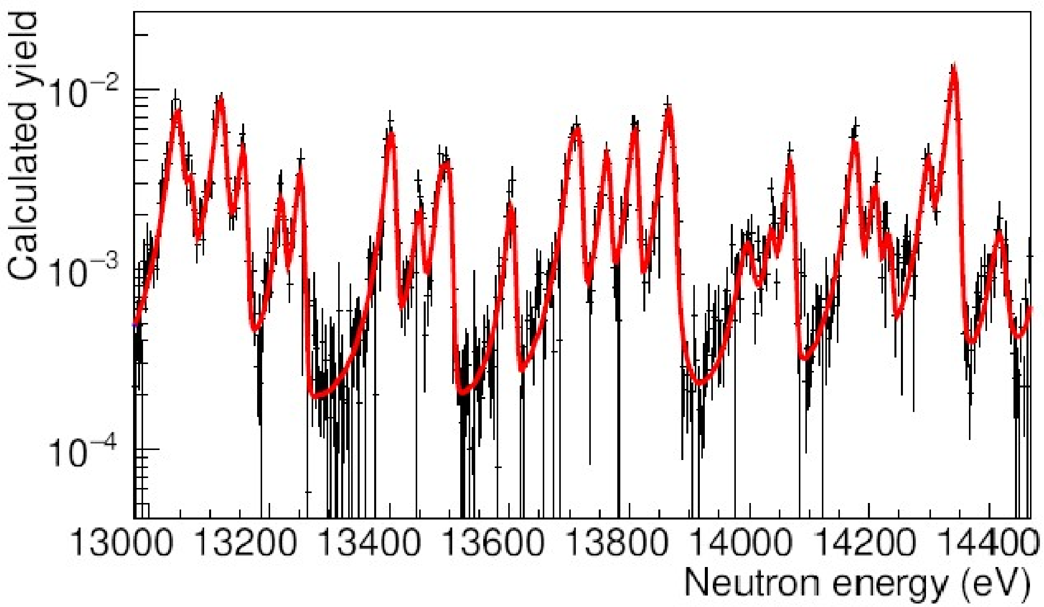
Capture TOF spectrum

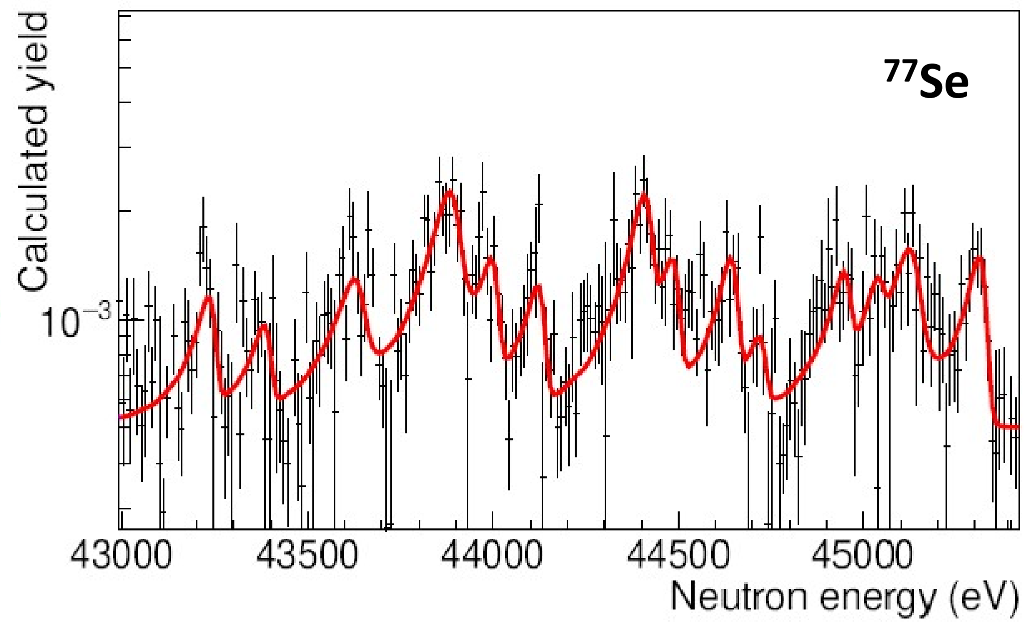


- Resonances allow "direct observation" of levels in the region of "high(er) NLD"
- Only restricted spin/parity range (due to the penetrability of neutrons with different orbital momentum *l*)
- Resonance spacing usually not determined by simple counting or resonances

Capture, i.e. (n,γ), yield for ^{95}Mo (target) from TOF facility LANSCE/FP14, DANCE detector

Capture TOF spectrum

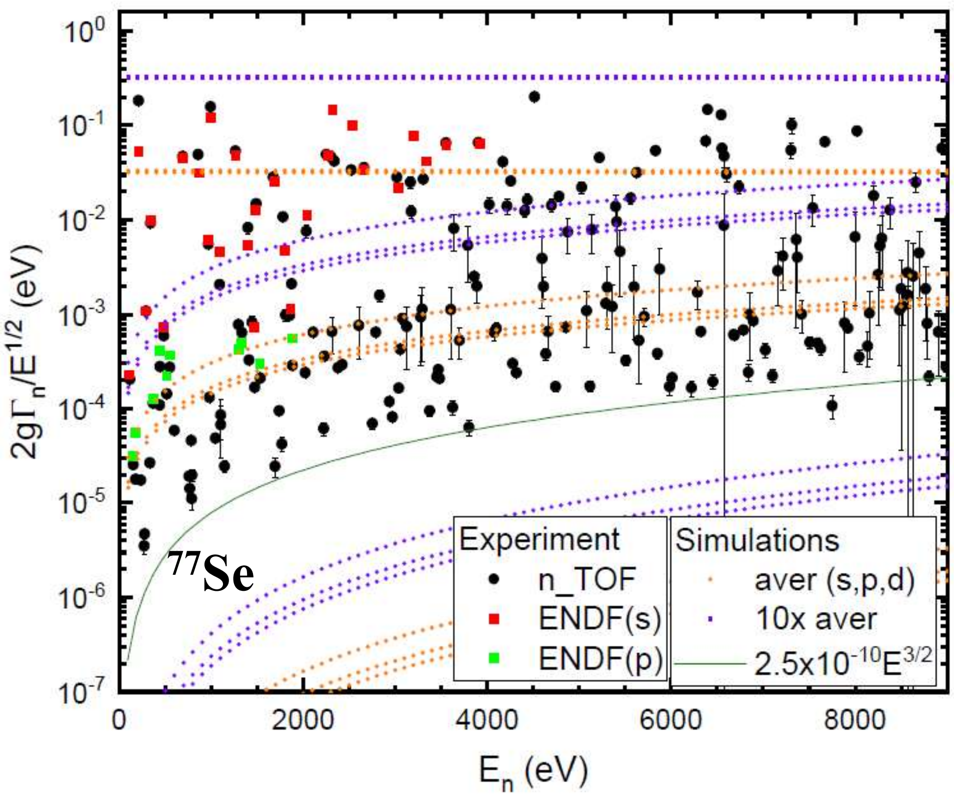




- n_TOF experimental data (together with SAMMY fit) from capture experiment on ^{77}Se

One can see structures but
- how many resonances do we miss?
- from capture measurement we have very limited info on J,π

Determination of D_0



- Resonances allow "direct observation" of levels in the region of "high(er) NLD"
- Only restricted spin/parity range (due to the penetrability of neutrons with different orbital momentum *l*) observed
  (although resonances for all spins present)
- Resonance spacing usually **not** determined by simple counting or resonances

- There is a "threshold" for observation (in Γ_n, or *k*) – typically increases with neutron energy (combination of flux decrease, more complex resolution function, …)
- The threshold is surely not really smooth – always dangerous to consider even smallest resonances

Data from N. Sosnin et al. (n_TOF coll.), PRC 107, 065805 (2023)

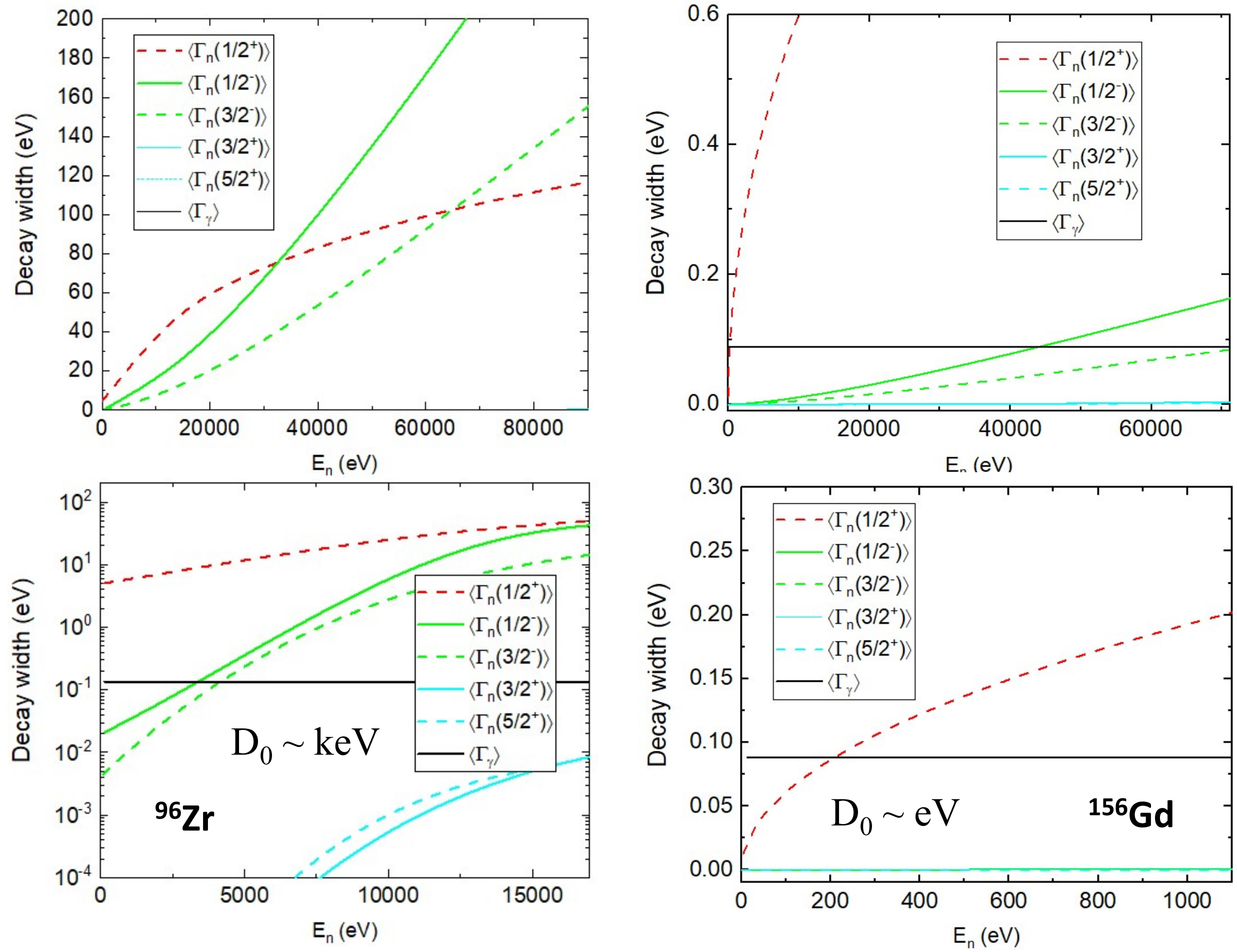
Resonances

It would be ideal to have resonance sequences with given π (for determination of D_0, D_1,…) and J

Each sequence should be

- **complete** (on the one hand) – problem everywhere but especially for D_0 in eV range
- **pure** of any contamination (on the other hand) – problem for D_0 in keV range

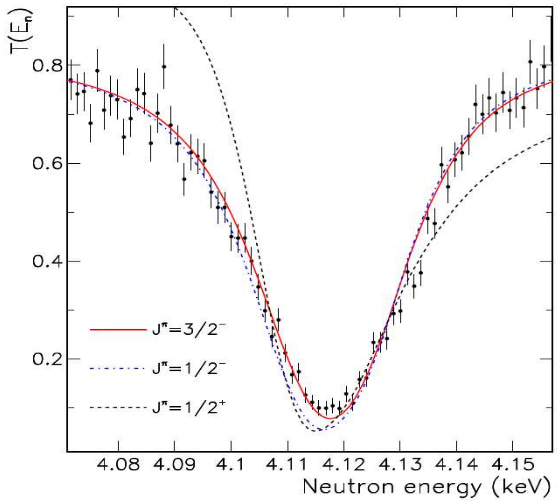
For nuclei with D_0~eV region, we can hardly see resonances with $l>0$ (s-wave)
(but sometimes visible)



Determination of l=0/l>0 – transmission for strong resonances

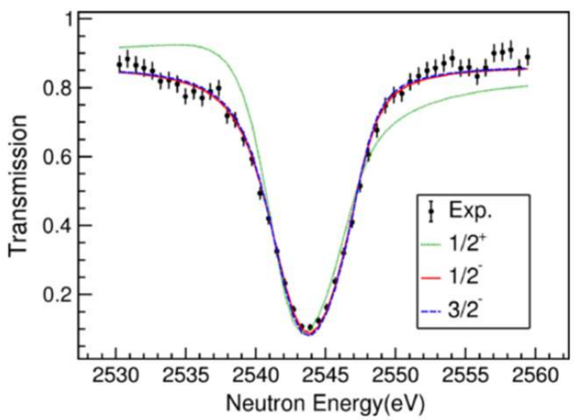
Transmission through the 17g ^{92}Zr sample, GELINA. Experiment compared with REFIT code fit for J^{π} = 1/2+, 1/2-, and 3/2-.

G. Tagliente et al. (n_TOF coll.), PRC **105**, 025805 (2022)



Similar: transmission through 35g ^{140}Ce sample, GELINA.

S. Amaducci et al. (n_TOF coll.), PRL 132, 122701 (2024)



If Γ_n **large enough**, π can be identified from transmission shape:

- the broadest *s*-waves - asymmetric
- *p*-waves - symmetric

For **smaller** Γ_n, π assignment difficult – the asymmetry not clearly visible

- If $g\Gamma_n$ is not too small, sometimes possible to assign π using both transmission and capture data – difficult to use simultaneous agreement between the fitted and data peak positions for "wrong assumed parity"
- practical applicability could be limited (depends on "resolution function")

Illustration of analysis results (GELINA + n_TOF, ^{92}Zr)

E_R (eV)	Γ_γ (eV)	Γ_n (eV)	J	ℓ	K (eV)	$\frac{\Delta K}{K}$ (%)
2011.25(9)	0.44(2)	0.0273(1)	3/2	1	0.0514	7.8
2684.66(7)	0.056(1)	24.78(4)	1/2	0	0.0554	2.3
4116.29(7)	0.208(3)	3.44(2)	3/2	1	0.392	2.0
4634.00(9)	0.062(2)	14.58(6)	1/2	0	0.0621	3.2
5039.9(2)	0.191(3)	1.23(3)	1/2	1	0.165	3.8
6632.2(3)	0.292(4)	1.28(3)	3/2	1	0.475	3.7
6794.6(2)	0.229(4)	73.4(2)	1/2	0	0.228	2.1
8835.7(3)	0.096(2)	3.71(8)	1/2	1	0.0935	4.4 †
9127.3(3)	0.067(2)	5.22(8)	1/2	0	0.0665	4.0
9815.9(2)	0.112(2)	1.67(6)	3/2	1	0.209	5.5 †
11935.7(5)	0.153(3)	2.3(1)	3/2	1	0.287	5.6
12005.4(4)	0.146(4)	8.3(2)	1/2	1	0.144	4.3 †
13059.8(7)	0.121(4)	2.1(1)	3/2	1	0.229	7.9
14414.2(6)	0.152(4)	12.6(2)	1/2	1	0.150	4.3 †
15021(3)				1	0.109	17 †
17116.1(7)	0.121(3)	11.0(2)	3/2	1	0.238	4.0
19064(3)	0.171(4)	2.7(2)	3/2	1	0.323	8.9
20188(9)	0.29(1)	1.0(3)	1/2	1	0.23	30 ×
20847(3)			1/2	1	0.34	14 †
21966(6)			1/2	1	0.28	16 †
23080.8(6)			1/2	0	0.11	18 †

G. Tagliente et al. (n_TOF coll.), PRC **105**, 025805 (2022)

E_R (eV)	Γ_γ (eV)	Γ_n (eV)	J	ℓ	K (eV)	$\frac{\Delta K}{K}$ (%)
25107(2)					0.033	51
25675(6)			1/2	1	0.097	18 †, ×
26765(9)			1/2	1	0.20	27 †
27322(1)	0.301(8)	18.2(6)	1/2	1	0.296	5.6 †
28071(3)			3/2	1	0.17	15.8
28149(2)	0.25(1)	18.2(6)	1/2	1	0.243	8.6
30361(7)					0.15	20
30922(3)	0.25(1)	11.4(5)	3/2	1	0.489	6.8 †
32468(5)	0.210(6)	9.7(6)	3/2	1	0.412	8.7 †
33098(7)			1/2	0	0.13	15 †
35031(4)	0.17(8)	49(2)	1/2	1	0.165	8.7 †
35670(3)	0.277(9)	52(2)	1/2	1	0.275	6.9
35939(4)				1	0.351	7.6
37536(16)				1	0.30	21 †
38737(2)			1/2	1	0.11	86 †
38931(2)	0.229(7)	6.0(7)	3/2	1	0.44	16
39326(4)			1/2	1	0.297	7.9 †
39479(4)			1/2	0	0.06	22 †
41225(14)			3/2	1	0.328	20 †
43759(2)			1/2	1	0.324	23 †
45079(3)	0.30(1)	82(2)	1/2	1	0.301	5.8 †
45754(3)	0.29(1)	28(1)	1/2	1	0.291	8.9 †
≈46900					1.04	2.1 Multiplet
47667(4)			1/2	0	0.202	8.6 †

Definite spin and parity can often be determined only for rather limited number of resonances

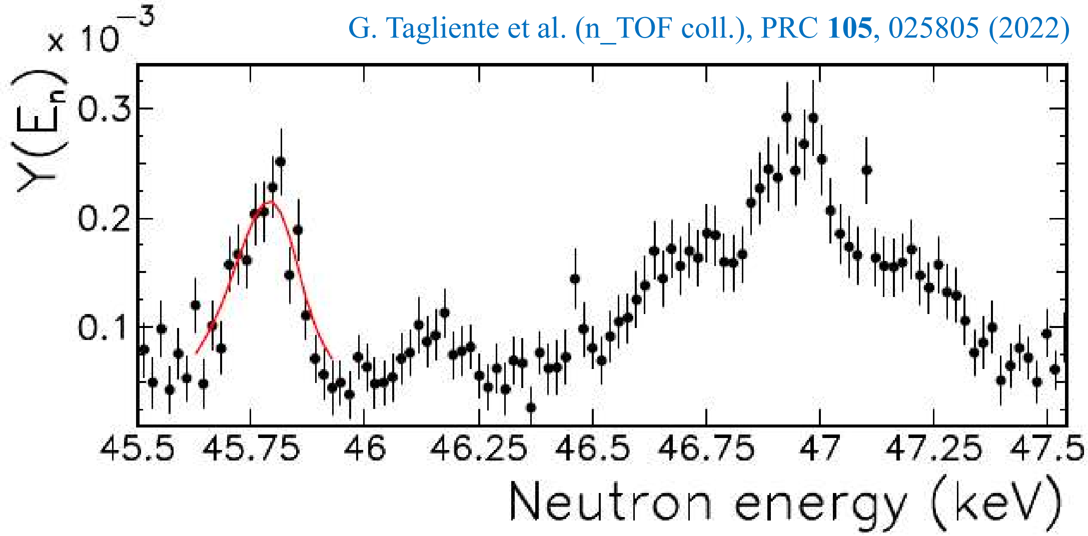
Is the spin and parity reliably determined in measurements from 70's/80's?
Surely in many cases …

Example of a resonance

Many nuclei measured in 70's (and 80's) "relatively routine measurements"

Not always surely correct … but hopefully not many mistakes (in parity assignment)

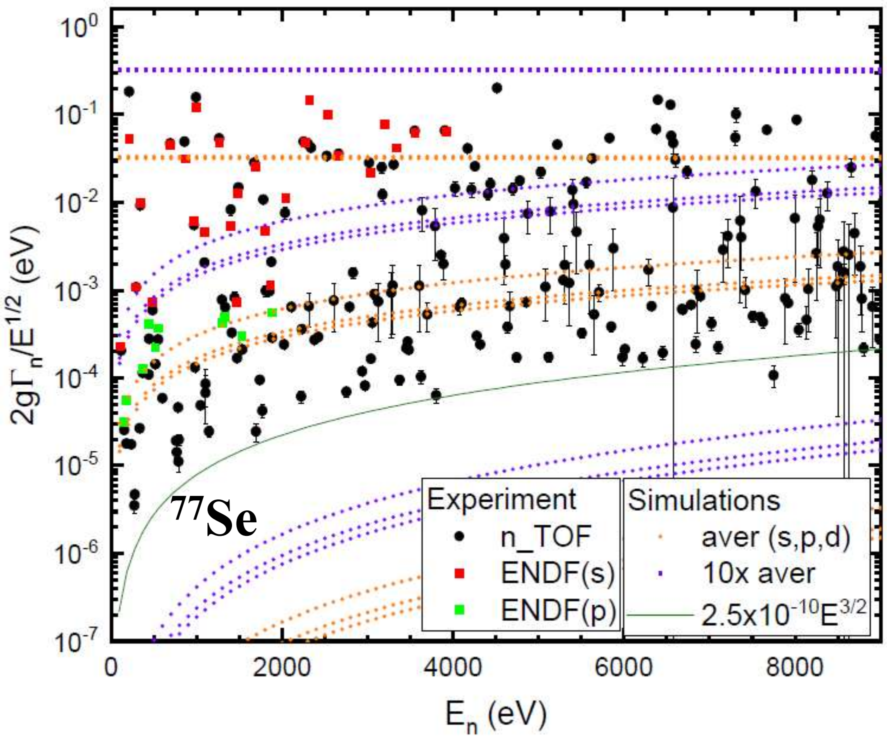
G. Tagliente et al. (n_TOF coll.), PRC **105**, 025805 (2022)



Experimental capture yield for the 10 g ^{92}Zr sample measured at GELINA.
Single resonance reported between 46.5 and 47.5 keV (ORELA).
At least triplet visible from GELINA data.

Determination of D_0

Determination of D_0

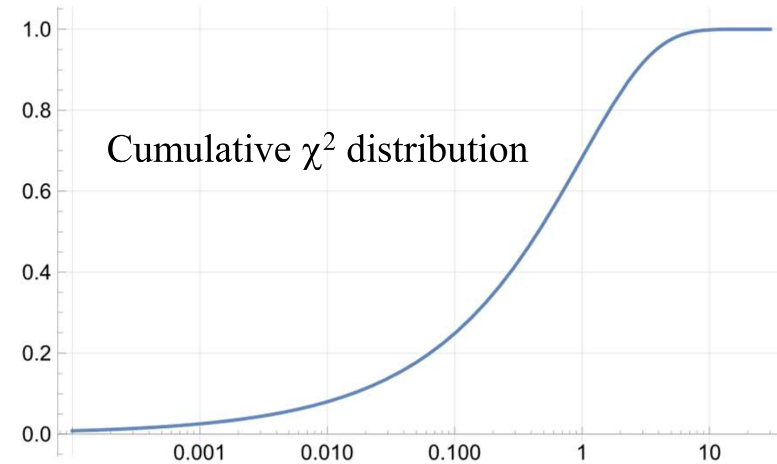


reliability of Γ_n in some regions of their values not very high if only capture data available, only *k* typically published

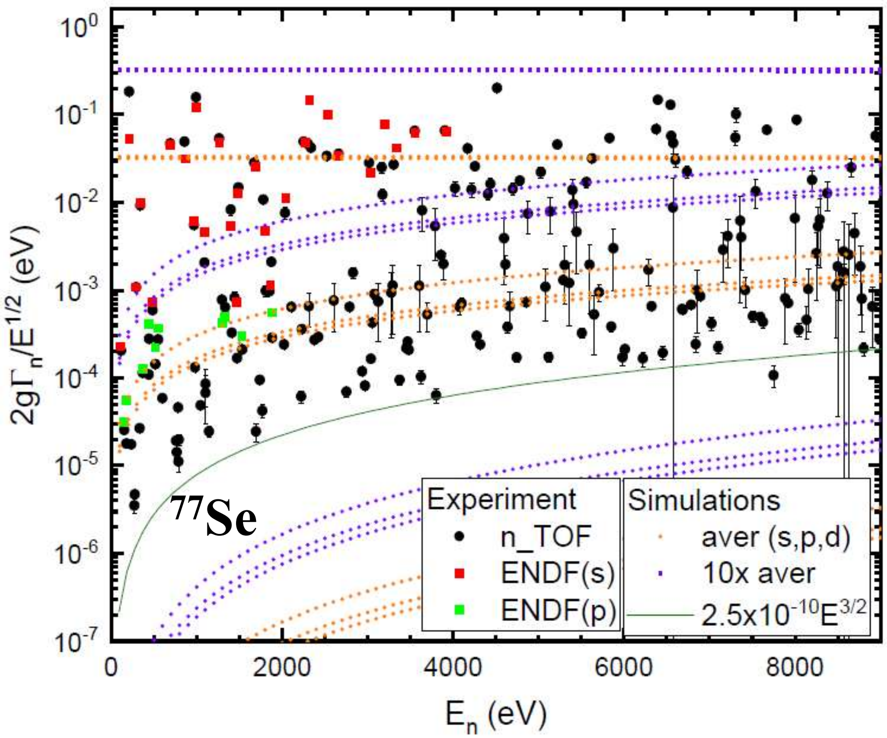
Data from N. Sosnin et al. (n_TOF coll.), PRC 107, 065805 (2023)

Parity for strong resonances can often be assigned using "statistical" model predictions

- Using different penetrability ⇒ separation of s- ($l=0$) and p-wave resonances in Γ_n (Γ_n^0) at low E_n
- Resonances above the "middle magenta lines" are (almost surely) s-wave ones
- If average resonance parameters close to reality, probability of a p-wave resonance above these magenta lines is about 0.2%.

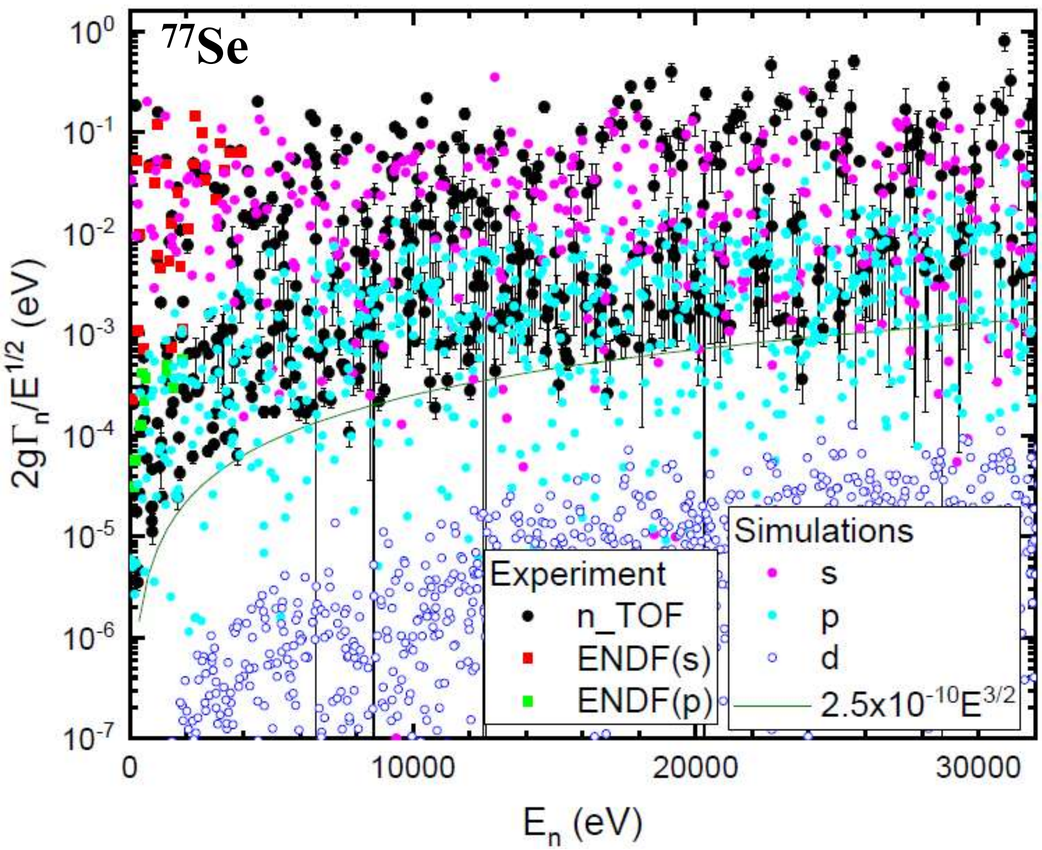


Determination of D_0



- If data on Γ_n (Γ_n^0) reliable, one usually tries to apply a threshold in this quantity and estimate the number of subthreshold resonances **assuming Porter-Thomas distribution** assumed/expected for (Γ_n^0)
- Estimate of S_l must be made (given by a sum of $g\Gamma_n^l$ within an interval – OK, but significant fluctuations if not many resonances!)
- This procedure traditionally applied, surely also for RIPL-3 evaluation (MK does not know details)
- Can be applied analytically or Monte Carlo
- At n_TOF we use Monte-Carlo approach – random resonance sequences generated for each tested D_0 and probability that observed number of resonances corresponds to the experiment is checked – uncertainty can be obtained

Determination of D_0

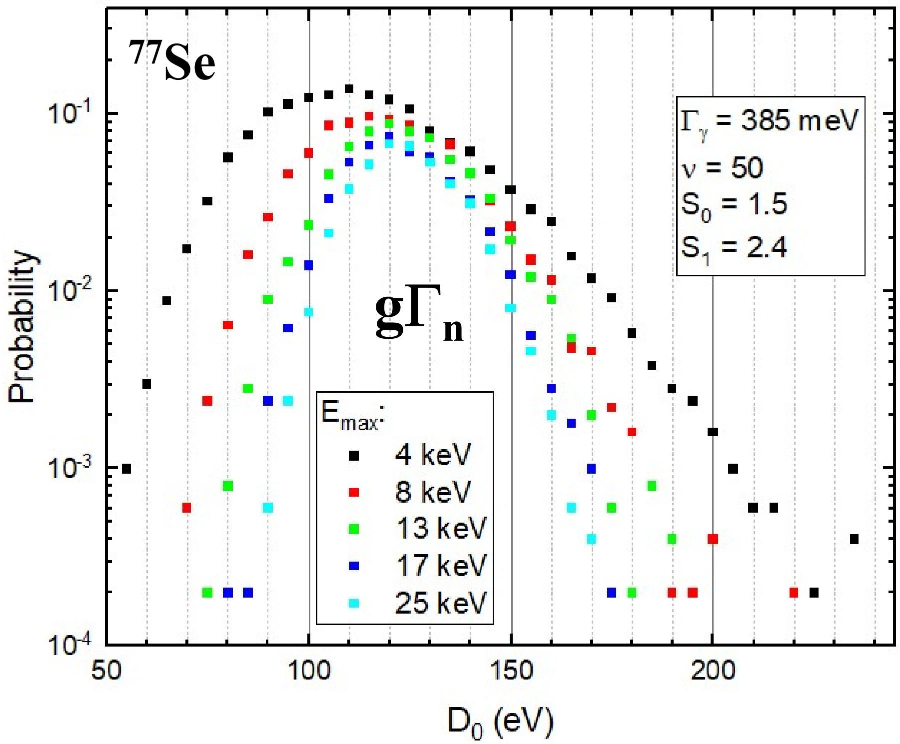


- Any threshold can be used
- Lower threshold means more resonances and leads to smaller error in D_0 determination but for many nuclei contribution of resonances with $l>0$ is significant

- If some p-wave resonances are above the threshold, an **assumption on spin- (and parity-) dependence** of level density **has to be applied**.

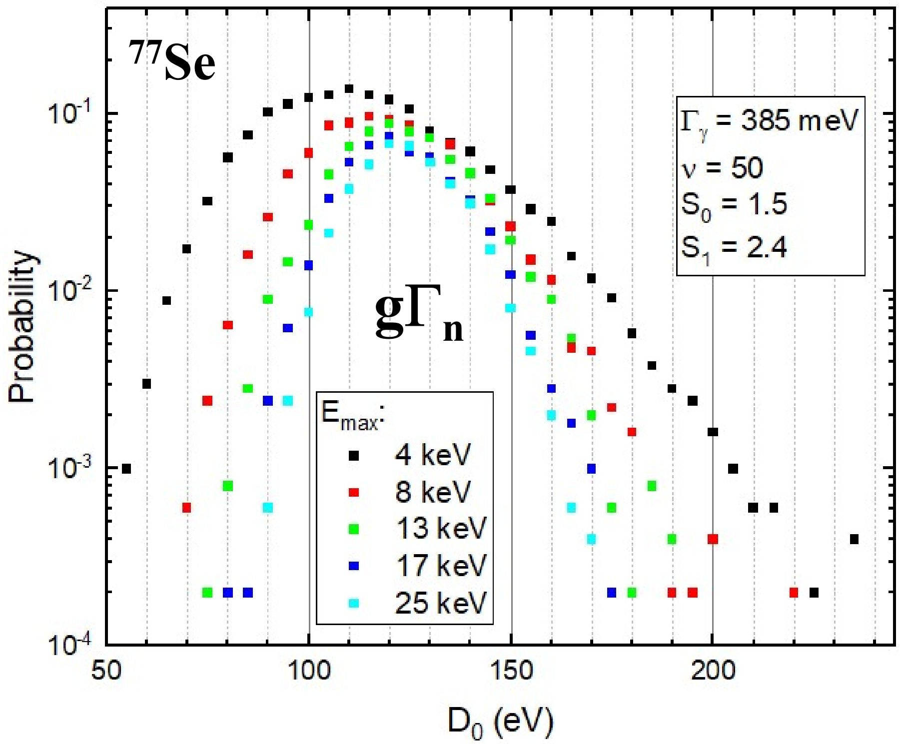
- Several different thresholds and/or maximum neutron energies can be checked.

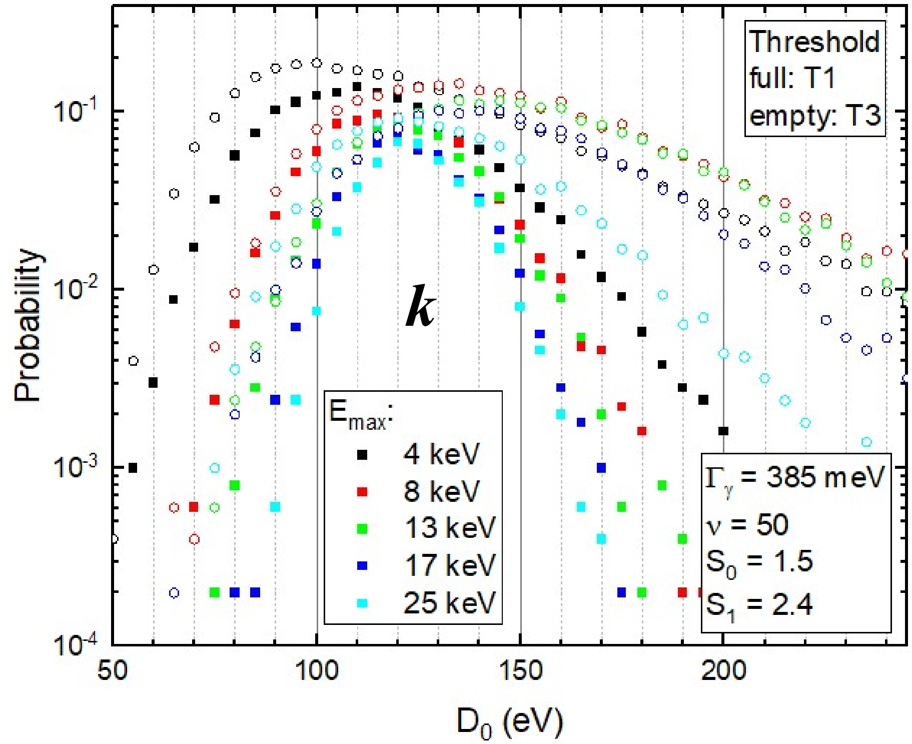
Illustration of MC analysis



Probability that for assumed D_0 the number of above-threshold resonances is the same in simulations and experiment

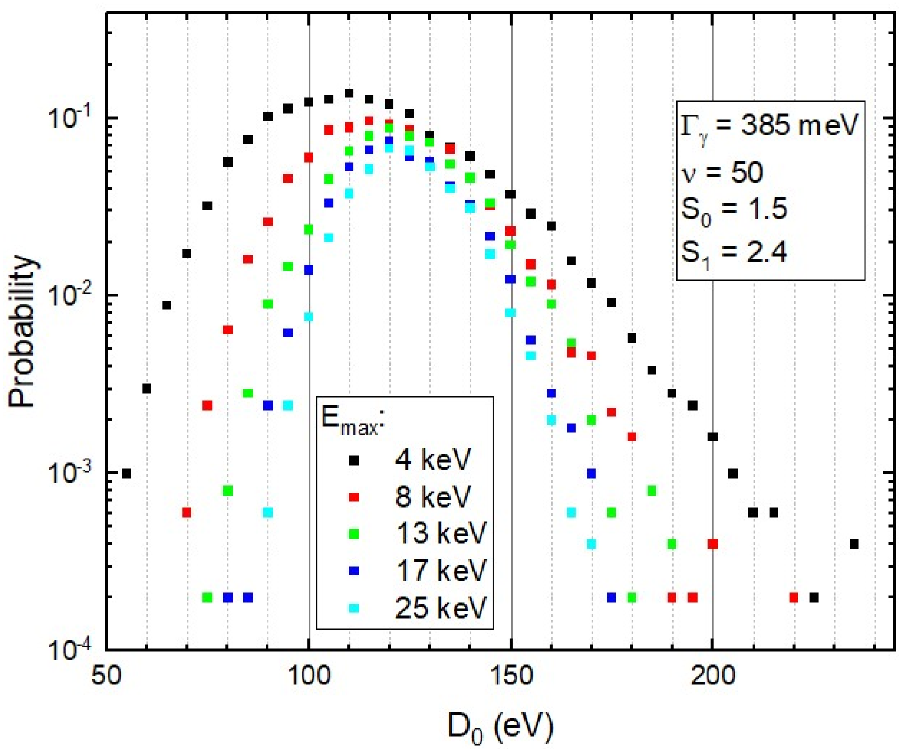
Illustration of MC analysis





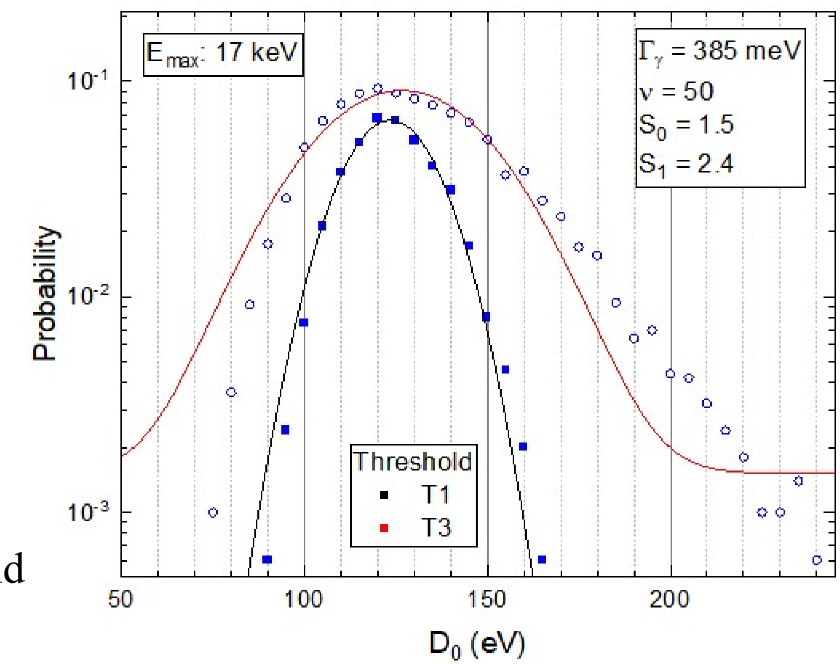
Probability that for assumed D_0 the number of above-threshold resonances is the same in simulations and experiment

If Γ_γ distribution assumed, k can be used



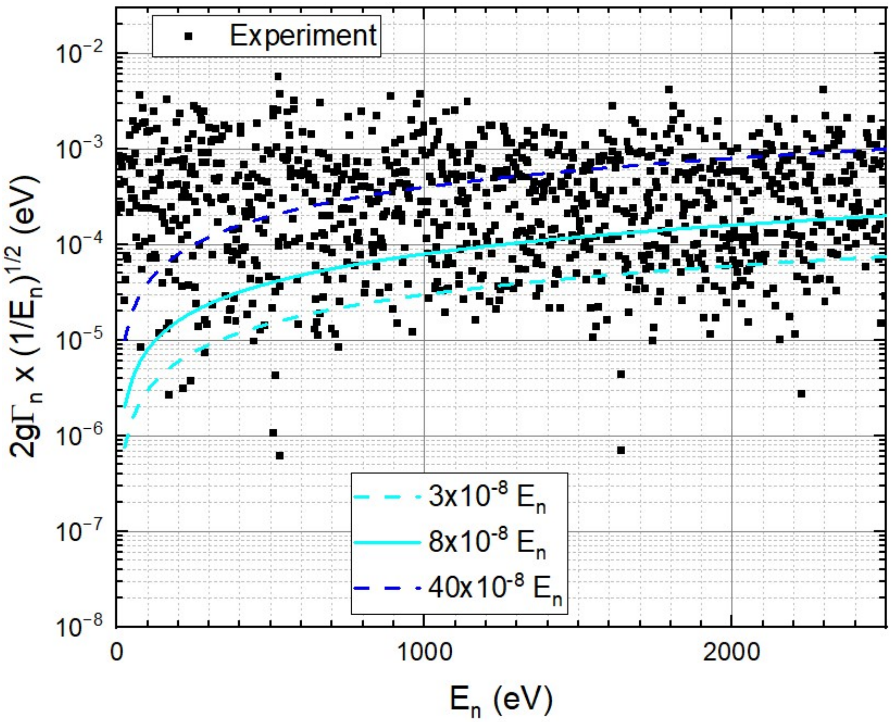
D_0 can be deduced from the distribution

- 68% central values
- Fit of a gaussian (+ small const) – typically used
- A combination of more thresholds, … (but strong correlation of individual values)



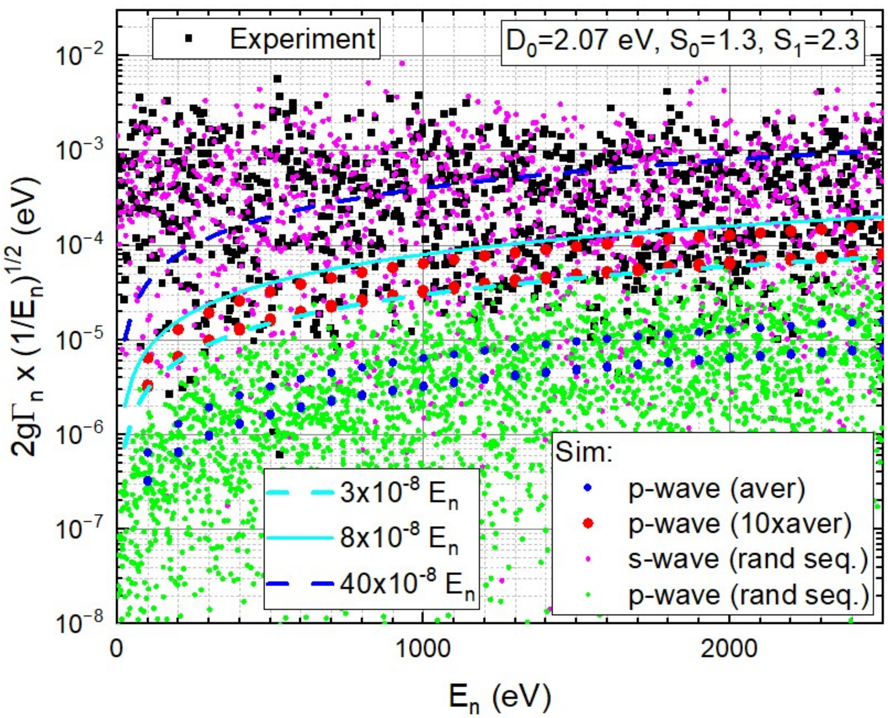
Probability that for assumed D_0 the number of above-threshold resonances is the same in simulations and experiment

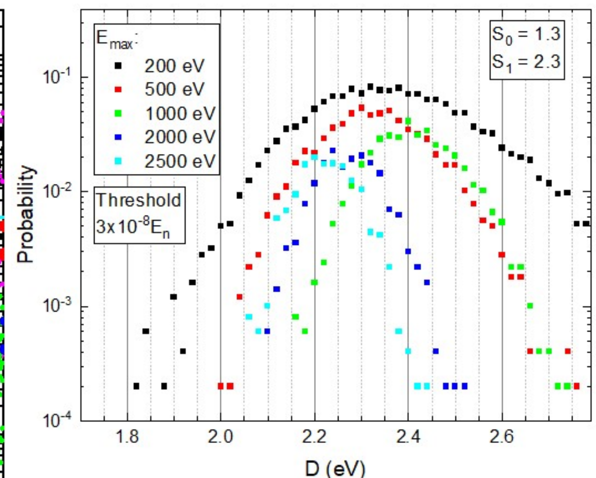
Nuclei with $D_0 \sim$ eV

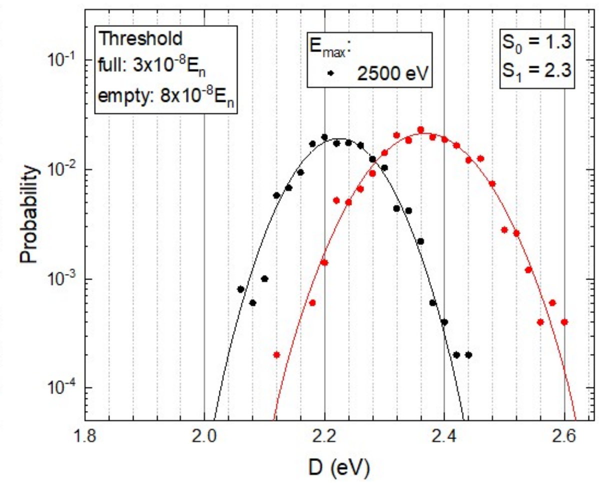


^{239}Pu target
(ENDF data – resonances listed up to 2.5 keV)

^{239}Pu (ENDF data)



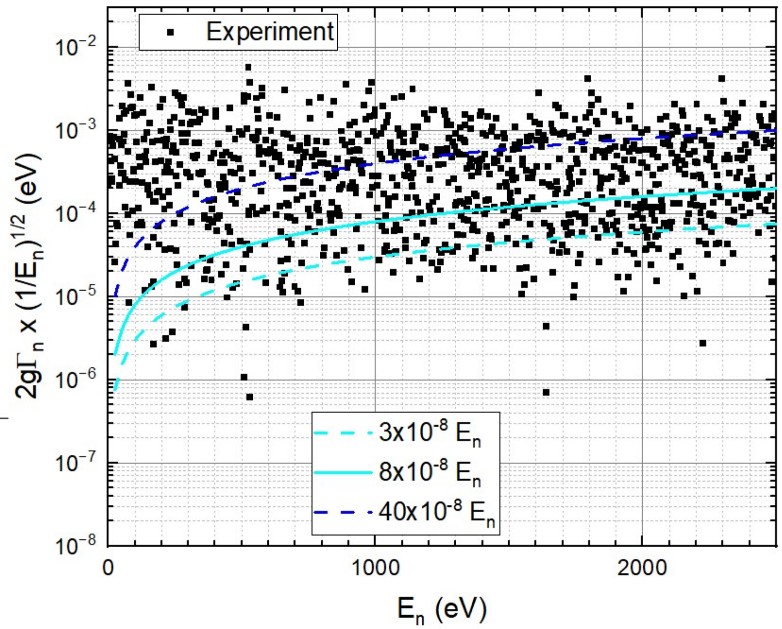


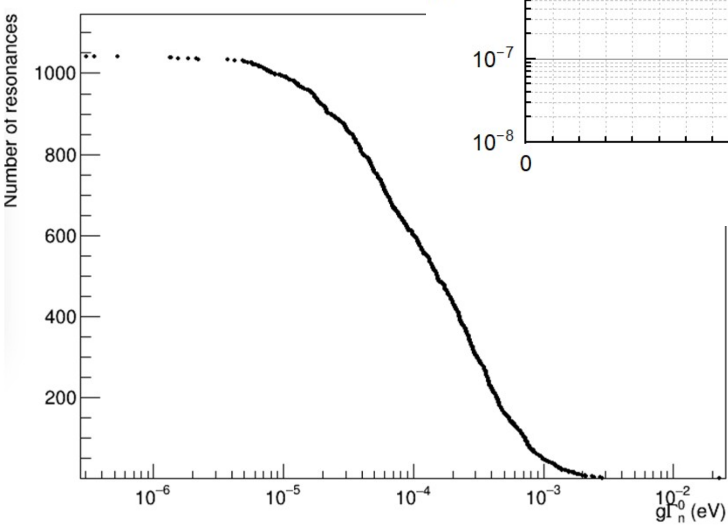


Threshold	Maximum Energy (keV)				
	0.2	0.5	1.0	2.0	2.5
	$S_0 = 1.3,\ S_1 = 2.3$				
$3\times10^{-8}E_n$	2.35(16)	2.32(11)	2.41(9)	2.27(7)	2.22(6)
$5\times10^{-8}E_n$	2.25(14)	2.26(10)	2.35(8)	2.29(6)	2.27(6)
$8\times10^{-8}E_n$	2.21(15)	2.26(11)	2.33(9)	2.35(8)	2.38(7)
$20\times10^{-8}E_n$	2.20(17)	2.26(14)	2.36(13)	2.45(12)	2.46(11)
	$S_0 = 1.2,\ S_1 = 2.3$				
$3\times10^{-8}E_n$	2.35(16)	2.31(11)	2.39(9)	2.25(6)	2.20(6)
$5\times10^{-8}E_n$	2.26(15)	2.25(10)	2.33(9)	2.26(6)	2.23(6)
$8\times10^{-8}E_n$	2.20(15)	2.25(11)	2.31(9)	2.31(8)	2.31(7)
$20\times10^{-8}E_n$	2.18(17)	2.24(13)	2.31(11)	2.36(11)	2.37(11)

RIPL-3: D_0=2.20(9) eV, S_0=1.2(1)
Mughabghab Atlas: D_0=2.07(7) eV, S_0=1.3(1)
MK approach: D_0~2.30(8) … assuming Wigner spacing (no GOE)

^{239}Pu (ENDF data)





One can apply some additional tests

- Fit of the cumulative distribution of $g\Gamma_n^0$ (determination of D_0 requires simulations)
- Maximum Likelihood estimate fit of $\langle g\Gamma_n^0 \rangle$

Threshold (in $2g\Gamma_n^0$)	Maximum Energy (keV) 1.0	2.0	2.5
	$\langle g\Gamma_n^0 \rangle$ (meV)		
$1 \times 10^{-8} E_n$	0.275(19)	0.237(11)	0.230(10)
$3 \times 10^{-8} E_n$	0.272(19)	0.233(11)	0.225(10)
$5 \times 10^{-8} E_n$	0.270(19)	0.237(12)	0.230(10)

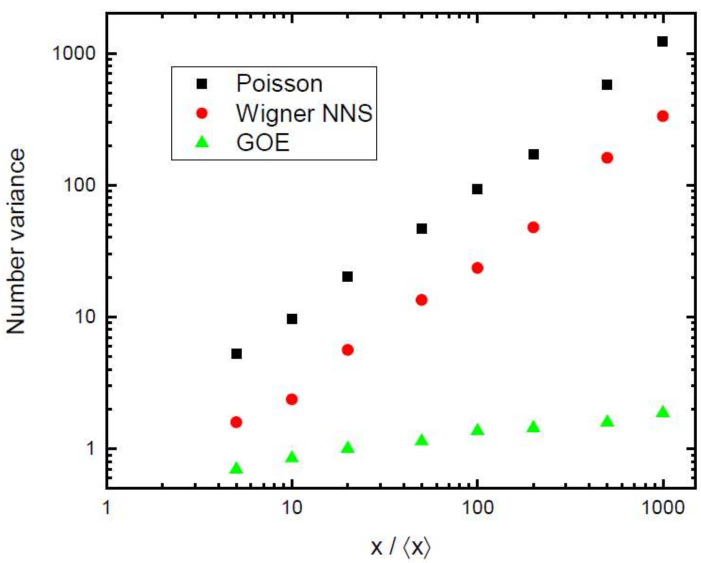
$\langle g\Gamma_n^0 \rangle = S_0.D_0$

- change in the product by about 20% (using data that are not independent)
- indicates some problems
- … for curiosity

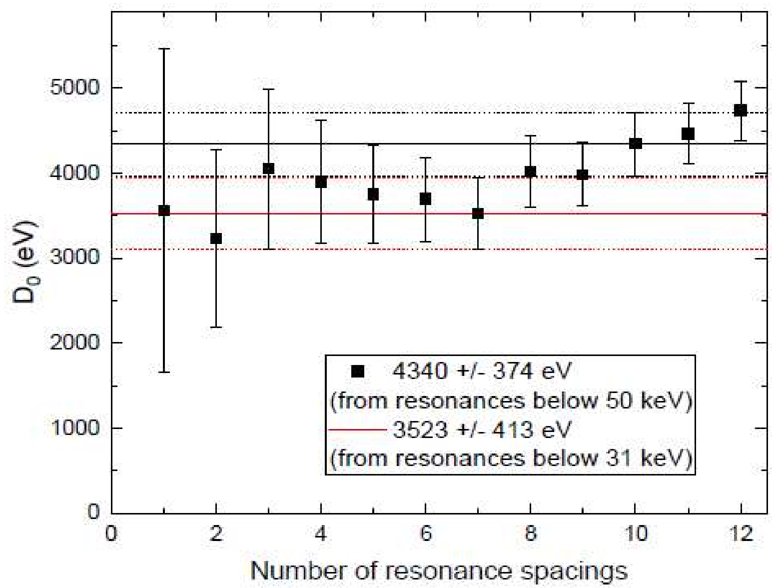
Can we exploit GOE predictions for determination of D_0?

Can we exploit GOE predictions for determination of D_0?

- If the resonance positions follow the predictions of GOE (long-range correlations) – spacing "can" be determined more precisely **if the sequence is complete (and pure)**
- Illustration via "number variance" - describes the (square of) fluctuations of number of levels within an interval.

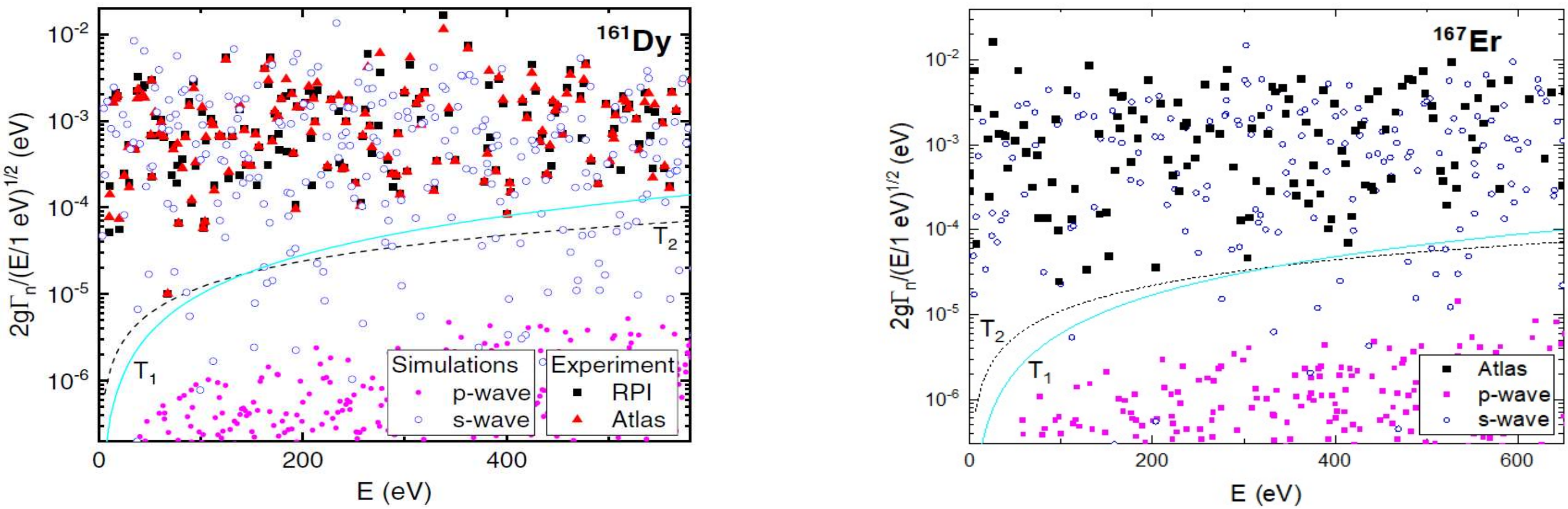


- Alternatively, we can check the position of n^{th} resonance with respect to the first (observed) one
- Illustration for ^{140}Ce target ($1/2^+$ res), uncertainties indicate standard deviation from GOE predictions



Completeness of sequences

Problem with sequence completeness (for all D_0) and purity (for larger D_0 nuclei)

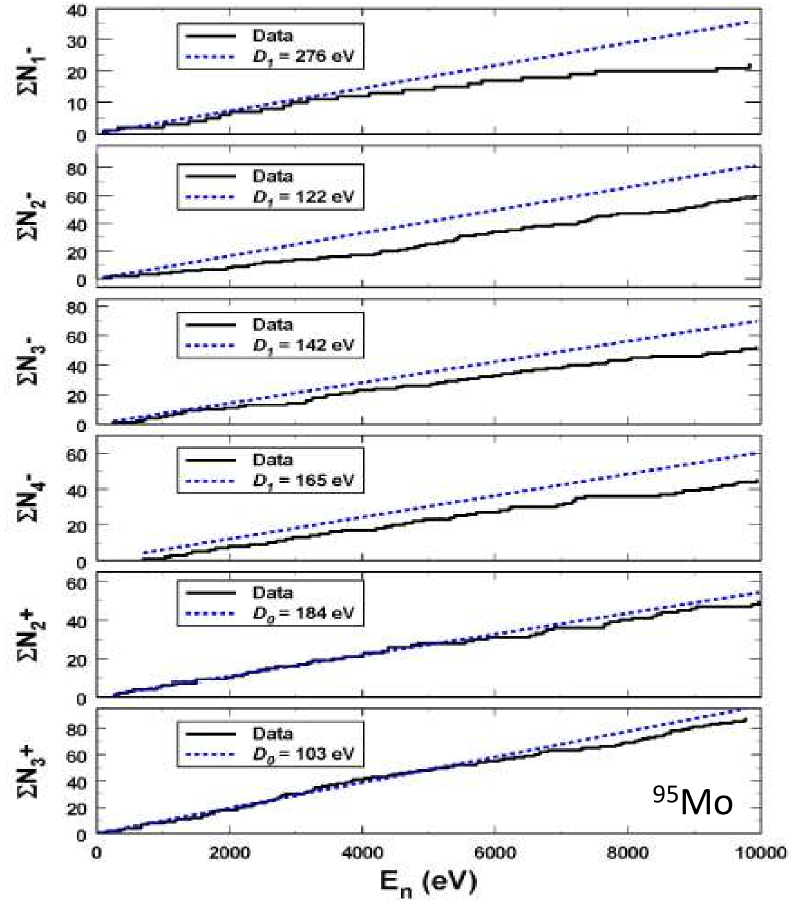


- Experimental data from Mughabghab's Atlas (and RPI)
- One random simulated sequence of resonances.

For Dy: D_0 = 2.15 eV, S_0 = 2.0×10^{-4}, D_1 = 1.16 eV, S_1 = 1.3×10^{-4}

How to check completeness?

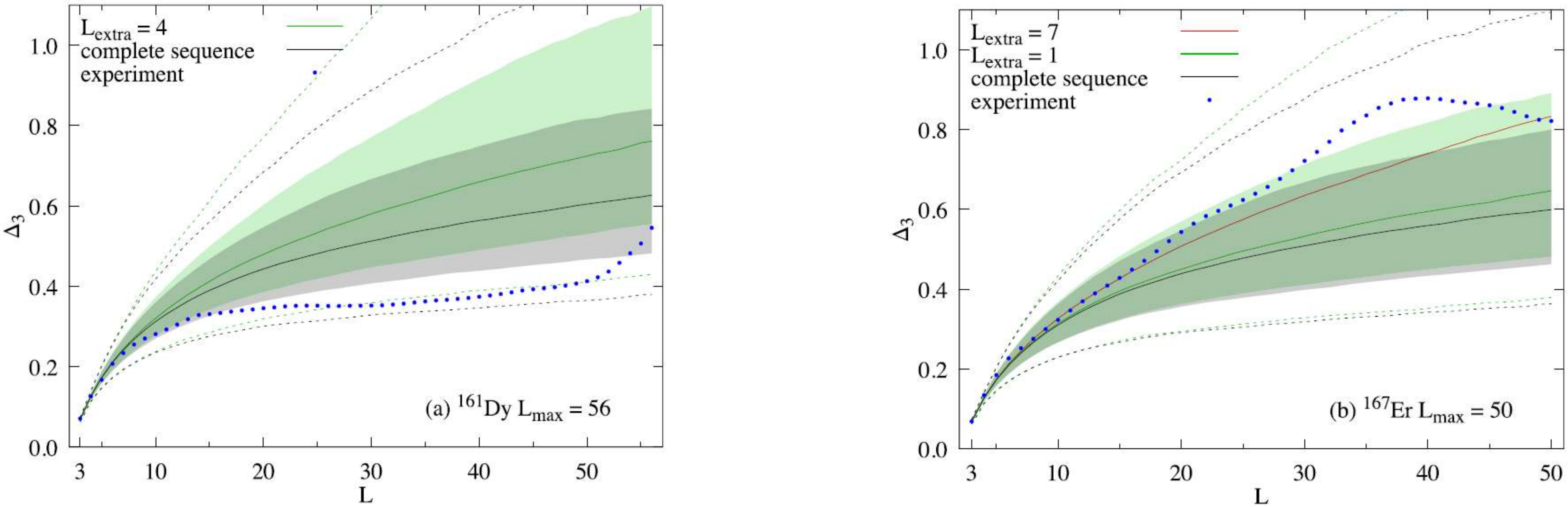
- The maximum energy where the sequence can be complete might be roughly estimated from a cumulative plot of resonances
- Only an estimate and we might miss resonances from very low energies



P. Koehler, PRC **105**, 054306 (2022)

How to check completeness? Tests based on GOE predictions

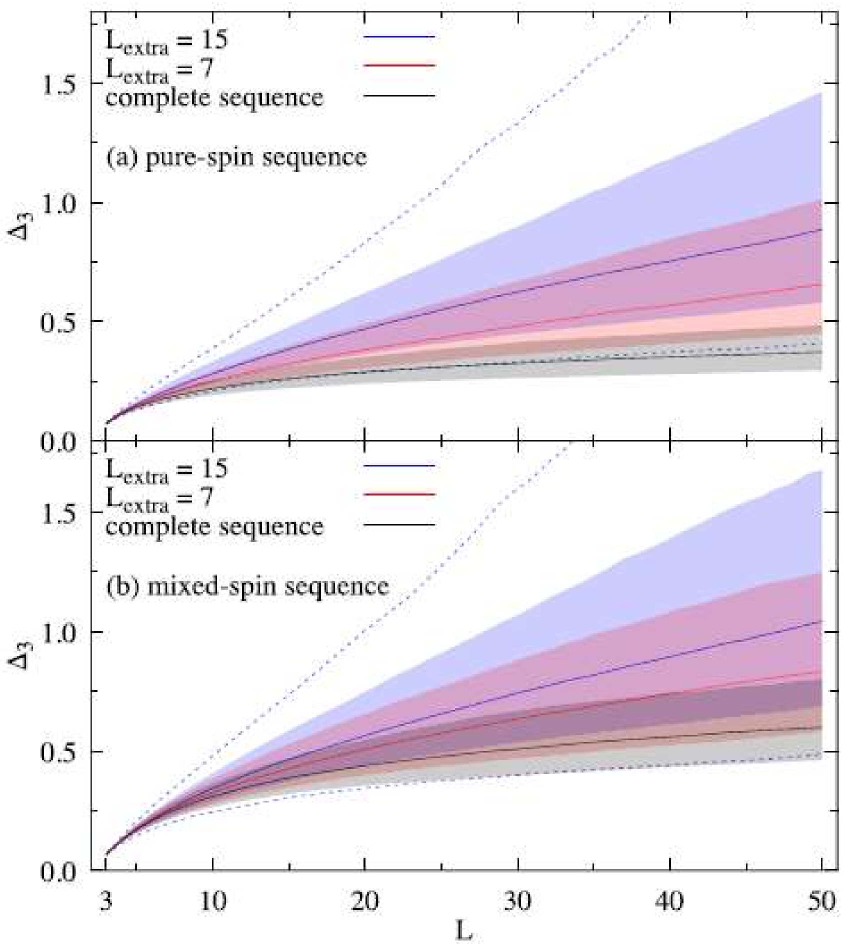
- Δ_3 statistic often used – a measure of fluctuation of positions around the “picket fence” (linear) dependence
- It shows up **not very sensitive for sequences of “realistic” length** (typically at most a few tens)



- $\Delta_3(L)$ for experimental mixed-spin sequences compared to their simulated counterparts
- Full lines – mean values (from simulations)
- Corridors form 68.27% central interval (~1σ), dashed lines 95.45% central interval (~2σ)
- L_{extra} … number of “missing resonances”

I. Knapova et al., PRC **106**, 034607 (2022)

Illustration of limited sensitivity

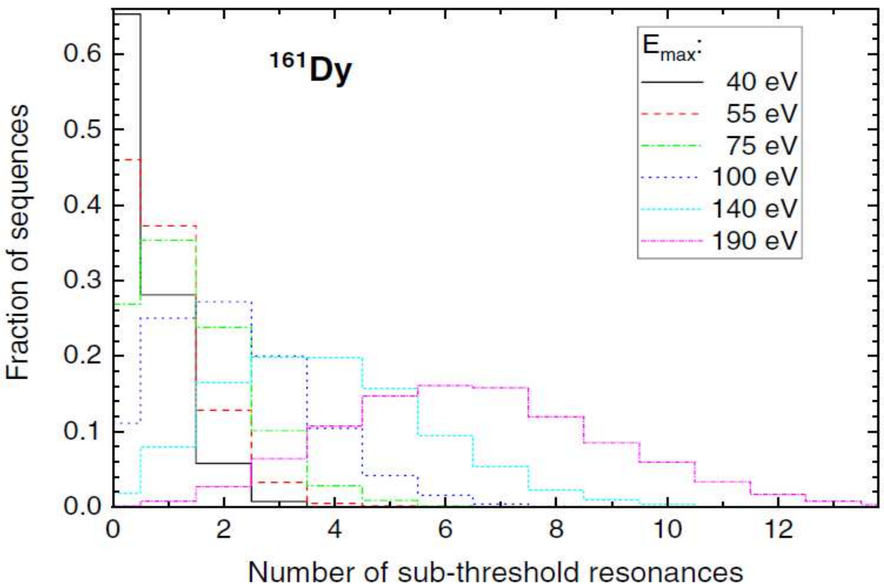


- The simulated $\Delta_3(L)$ for sequences with $L_{\max}$ = 50 and L_{extra} = 0, 7, and 15.
- The shaded corridors correspond to 68.27% central interval and the dashed lines for L_{extra} = 15 show 95.45% central interval.

I. Knapova et al., PRC **106**, 034607 (2022)

Possible approach for some nuclei

If average resonance parameters are known, estimate of sub-threshold resonances can be made



Distribution of number of sub-threshold *s*-wave resonances for a few max E_n in ^{161}Dy and T_1 threshold. (D_0= 2.15 eV and S_0= 2.0 × 10^{-4} used)

Nucleus		Threshold	$F_0^m \times 10^3$/Mode		
	E_{max} (eV)		86	135	209
^{161}Dy		T_1	179/1	21/3	<0.1/8
		T_2	100/2	10/4	<0.1/8
	E_{max} (eV)		215	290	402
^{163}Dy		T_1	187/1	54/2	6/5
		T_2	170/1	59/2	10/4
	E_{max} (eV)		135	200	285
^{167}Er		T_1	280/1	84/2	12/4
		T_2	152/1	37/3	4/5

Fraction of complete (mixed-spin) sequences F_0^m and the mode of distribution for different E_{max} and both thresholds on the previous slide.

Simple relation to individual spin sequences found.

I. Knapova et al., PRC **106**, 034607 (2022)

Possible approach for some nuclei

Deduced average resonance spacing from analysis of DANCE data using GOE assumptions and missing resonances (see above)

	E_{max}(eV)	D_0^-(eV)	D_0^+(eV)	D_0(eV)
^{161}Dy	86	4.56(28)	3.53(18)	2.04(8)
	135	4.74(29)	4.03(21)	2.25(7)
	209	5.14(24)	3.61(9)	2.15(5)
^{163}Dy[a]	215	11.69(73)	11.06(82)	5.95(28)
	290	14.07(83)	10.82(68)	6.34(28)
	402	13.70(60)	10.75(57)	6.39(24)
^{167}Er	135	7.46(51)	7.87(58)	3.72(19)
	200	8.49(50)	6.87(34)	3.79(15)
	285[b]	9.03(48)	6.70(25)	3.86(12)

[a]Doublet considered around 55.85 eV.
[b]204 eV 4^+.

Comparison of D_0 deduced from DANCE analysis (with highest E_{max}) with literature data

	D_0 (eV)		
Source	^{161}Dy	^{163}Dy	^{167}Er
DANCE	2.15(5)	6.39(24)	3.86(12)
Liou *et al.* [7,41]	2.67(13)	6.85(54)	4.06(17)
Shin *et al.* [39]	2.59(1)	6.90(8)	
Shin *et al.* [40]	2.31(23)	6.91(59)	
Mughabghab [10]	2.08(15)	6.99(30)	3.80(21)
RIPL-3 [46]	2.40(20)	6.80(60)	4.20(30)

Small uncertainty comes from the fact that the number of sub-threshold resonances is likely rather small. If larger – the uncertainty increases.

I. Knapova et al., PRC **106**, 034607 (2022)

Are GOE predictions justified?

Not 100% clear – some deviations reported (mainly works by P.E. Koehler in last about 15 years)
MK involved in some of them. For instance,

- Experimental data on reduced neutron widths showed a very low probability that they could be consistent with Porter-Thomas fluctuations; P.E. Koehler at al., PRL 105, 072502 (2010)
- If correct, would have a significant impact on actual NLD (D0)
- MK is not sure if he believes in this effect but if experimental data correct, the effect is there

- There are also some problems with long-range correlations in “Nuclear Data Ensamble” (NDE)
  P.E. Koehler at al., Fortschritte der Physik-Progress of Physics 61 (2-3) , pp.80-94

- P.E. Koehler reported a few more cases …

- In general problem with experimental data – spin/parity of resonances in NDE were likely assigned assuming the validity of GOE by experimentalists … (above-discussed problems)

Total radiative width

Total radiative width

Available information from isolated resonances

- sometimes not very rich in nuclei with D_0 in eV range (if Γ_n at low energies smaller or comparable to Γ_γ)
- typically, only $g\Gamma_\gamma$ obtained from individual resonances if D_0 in keV range (OK if J_T=0 and we know that $l=0$)
- Many values suffer from significant uncertainty
- Only resonances with "reliable" Γ_γ (certain relation to Γ_n, k) should be used

Alternatively, a piece of information might be obtained from **fitting the cross section in "unresolved region"** (FITACS)
(to high degree given by "Gg/D" … but contribution of different l)
the solution is often not very "stable" and the results must be taken with caution (personal experience of MK)

Γ_γ can have a relatively broad distribution (expected from statistical model)

E_0 (eV)	J	l	$g\Gamma_n$ (meV)	Γ_γ (meV)
−434	1/2	0		(65.8)
139.8±0.2	1/2	0	133 ± 8	77 ±16
180.3±0.1	1/2	0	220 ± 12	80 ±20
201.5±0.2	1/2	0	13.2± 1.0	
323.7±0.3	1/2	0	6.2± 1.0	
459.3±0.3	1/2	0	41 ± 5	
508.7±0.3	1/2	0	240 ± 20	60 ±20
544.4±0.4	1/2	0	27 ± 8	
619.6±0.4	1/2	0	93 ± 7	
662.0±0.5	1/2	0	55 ± 7	
753.8±0.6	1/2	0	810 ± 50	
815.4±0.6	1/2	0	214 ± 25	
859.2±0.4	1/2	0	28 ± 5	
875.6±0.4	1/2	0	69 ± 9	
981.4±0.4	1/2	0	23 ± 5	
1066.7±0.5	1/2	0	330 ± 40	
1129.4±0.5	1/2	0	42 ± 7	

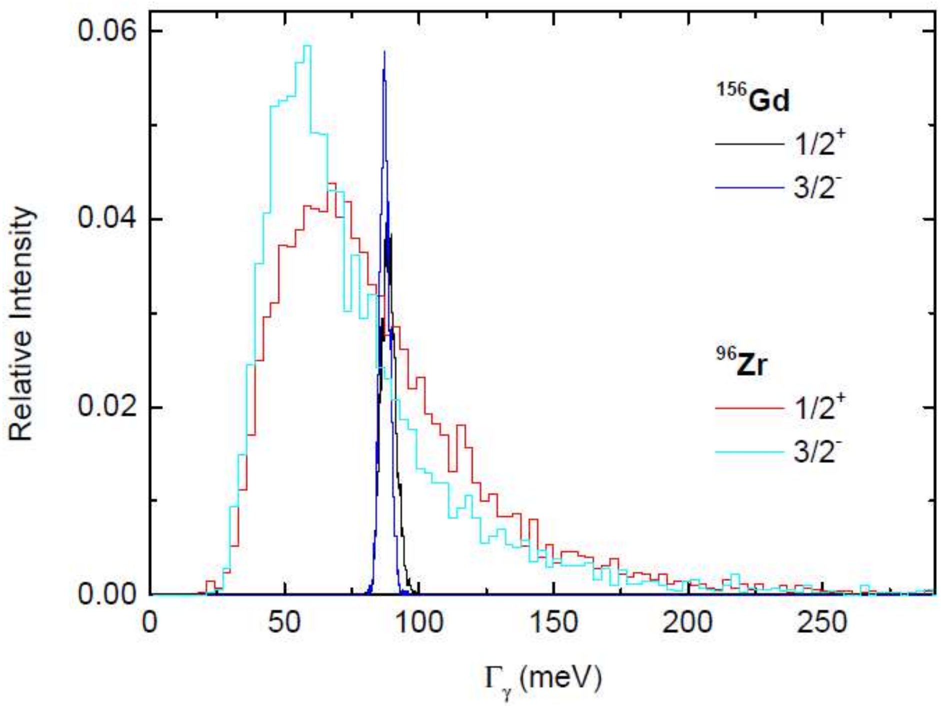
172Yb

RESONANCE PROPERTIES

D_0=75.7±4.2 eV
S_0=1.73±0.27
S_1=1.0±0.3
S_2=1.7±0.5
$\langle\Gamma_{\gamma 0}\rangle$=0.073±0.011 eV
$\langle\Gamma_{\gamma 0}\rangle^u$ =0.0805±0.0012 eV
$\langle\Gamma_{\gamma 1}\rangle^u$ =0.0629±0.0010 eV

RIPL3: Gg =77(10) meV

Expected distributions



Expected Γ_γ distributions from DICEBOX simulations

- Illustration for one model of PSFs and NLD
- Width of distribution depends on NLD
- Consists of many small contributions (partial widths)

E_0 (keV)	J	l	$g\Gamma_n$ (eV)	Γ_γ (eV)
−1.9	1/2	0		(0.06)
0.30129±0.00030	1/2	1	0.2150± 0.0025	0.239±0.007
0.8695 ±0.0009		[1]	0.0022± 0.0010	
3.8205 ±0.0040	1/2	1	3.93 ± 0.06	0.037±0.002
4.1353 ±0.0040	3/2	1	14.9 ± 0.2	0.053±0.003
5.4455 ±0.0050	1/2	0	25.3 ± 0.5	0.058±0.002
5.9749 ±0.0060	3/2	1	11.6 ± 0.6	0.092±0.003
9.009 ±0.009	[1/2]	1	9.9 ± 0.4	0.047±0.003
13.286 ±0.013		1	6.0 ± 0.4	0.040±0.004
15.151 ±0.015		1	9.2 ± 0.5	0.174±0.006
15.432 ±0.015	1/2	0	66.1 ± 1.5	0.077±0.009
17.791 ±0.018	3/2	1	16.1 ± 1.0	0.113±0.011
24.703 ±0.025	1/2	0	13.6 ± 1.5	0.035±0.005
29.815 ±0.030	[3/2]	1	584.0 ± 1.2	0.341±0.025
35.186 ±0.035	1/2	[0]	121 ± 5	0.145±0.032
36.671 ±0.037	[3/2]	1	141 ± 6	0.102±0.022
[a]41.510 ±0.042		1	36 ± 14	
[a]53.980 ±0.054	1/2	0	216 ± 28	
[a]55.201 ±0.055	1/2	1	430 ± 35	
[a]59.336 ±0.059		1	228 ± 25	
[a]63.699 ±0.064		1	29 ± 6	

^{96}Zr

RESONANCE PROPERTIES

D_0=12.8±2.0 keV
D_1=4.5±0.5 keV
S_0=0.34±0.14
S_1=6.0±1.8
$\langle\Gamma_{\gamma 0}\rangle$=0.071±0.008 eV
$\langle\Gamma_{\gamma 1}\rangle$=0.151±0.075
$\langle\Gamma_{\gamma 1}\rangle^u$ =0.1746±0.009 eV

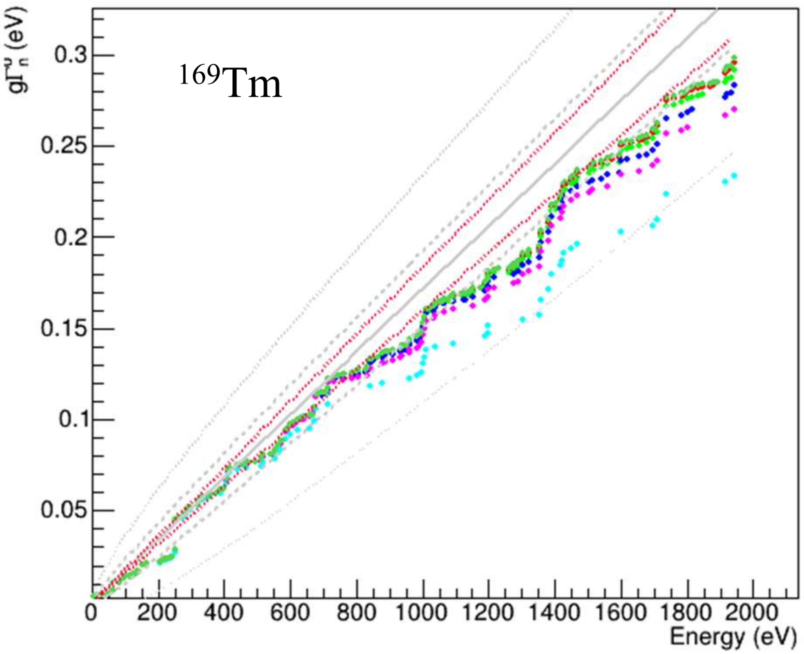
RIPL3: Gg=65(15) meV

Neutron strength functions

Neutron strength functions

Can be determined from neutron resonances (simultaneously with D0 and Γ_γ)

$$S_0 = \sum_\lambda g\Gamma^0_{n,\lambda}/\Delta E$$



Strong fluctuations (from Porter-Thomas fluctuation):

$$\Delta S_0/S_0 = \sqrt{2/N}$$

- Missing strength usually very small (for l=0)
- Can be corrected for
- Corrections for S_1 more complex
- S1 can be estimated even without fully correct parity resonance assignment, but then it suffers from larger uncertainty

Request from Consultants Meeting

Resonance spacing data

- Comprehensive compilation of all D_0 and D_1 that have been determined and published
  - Idea is to start with data (resonance parameters) in databases (ENDF, JENDL, JEFF), then search for new data
    (n_TOF, GELINA, CSNS?, LANSCE/DICER?)
  - A help from someone is needed

- Evaluation of compiled D_0 and D_1 values and recommendation of best values with associated uncertainties – including documentation of how the values were determined;
  - At least for D_0 – work in progress – many nuclei, the process must be as much as possible "automatic"
  - In some nuclei we are (almost) sure that the resonances are only s-wave ($l=0$)

  - For D_1: in principle the same, but all $l=0$ resonances must be eliminated

Request from Consultants Meeting

Resonance spacing data

- Comparison of different methods to determine resonance spacing data and related uncertainties for selected cases if not all;
  - Work in progress – several different ways of spacing determination are to be compared – at least for some nuclei – D_0 from Γ_n, kernel, considering GOE sequences, fit to the cumulative Porter-Thomas distribution (requires some simulations)
  - Uncertainties from different methods are planned to be compared

- Provide D_0 for ($l+1/2$) and D_0 for ($l-1/2$) if available and possible
  - Sometimes possible, there exist (relatively reliable) methods to determine spin of a resonance in some nuclei

  - It is very difficult to verify all spins/parities of reported resonances
  - Corrections to missing levels can be reasonably done, but it is crucial to have good data – not an easy task

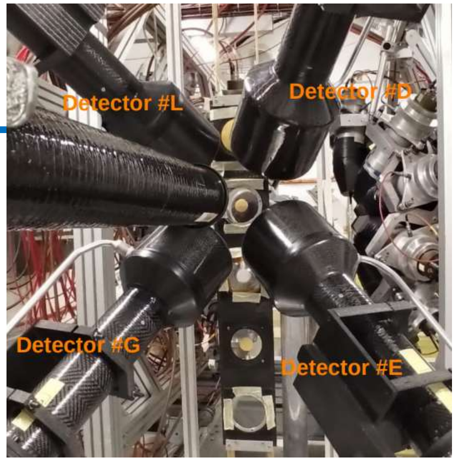
Spin of neutron resonances

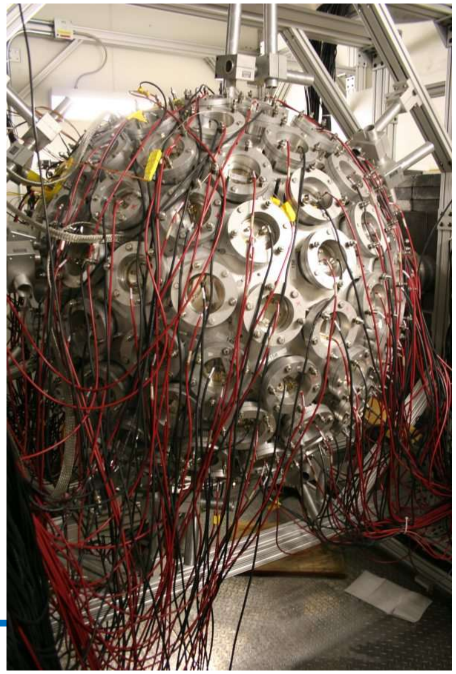
Can be determined by several methods (very crude division)

1) analysis of transmission, scattering, or capture cross-section measurements (above)
2) measurement of transmission using polarized neutrons and samples
3) detection of differences in γ-ray spectra from resonances with different spins

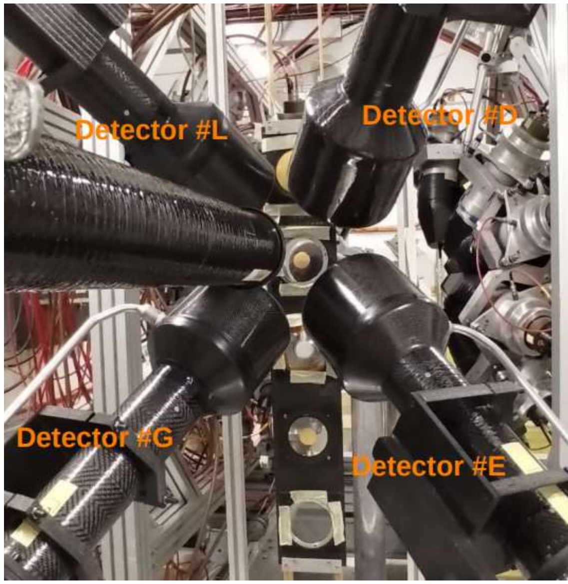
- ratio of singles to coincidence from two scintillation detectors
- intensities of γ rays from low-lying levels measured with Ge detectors,
- the singles/singles, and coincidences/coincidences ratios for different pulse-height regions with C_6D_6 detectors,
- cascade characteristics measured with 4π segmented detector arrays, e.g., DANCE or TAC at n_TOF
- …

Mughabghab Atlas lists 9 methods, but those can be combined into these groups



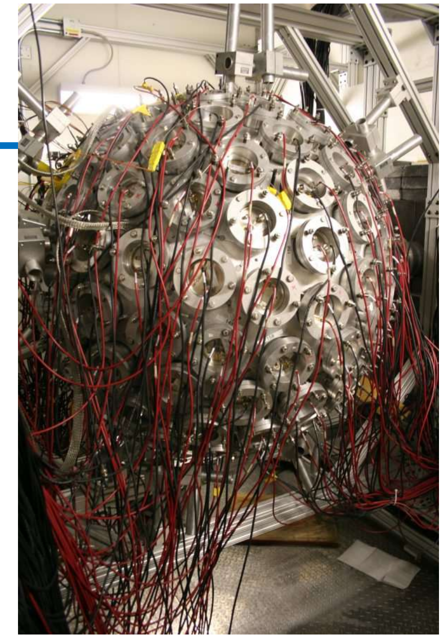


Detection systems

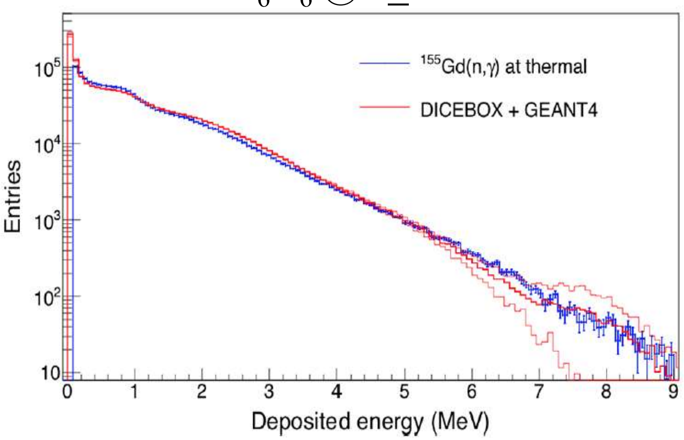


Traditional detection systems:

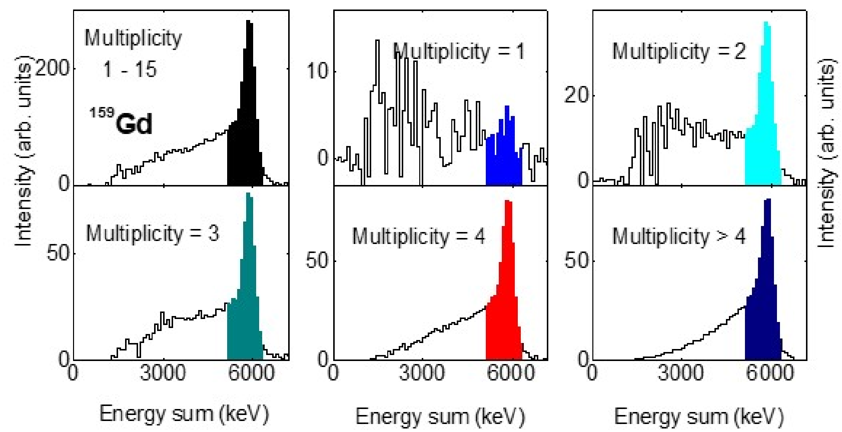
- Low-efficiency detectors (usually C_6D_6) in combinations with “Total-energy deposition + Pulse-Hight Weighting Techniques” – at maximum one photon from a cascade is detected
- High-efficiency detectors (BaF_2 spheres)
- Other detection systems under development (@ n_TOF – sTED, iTED)



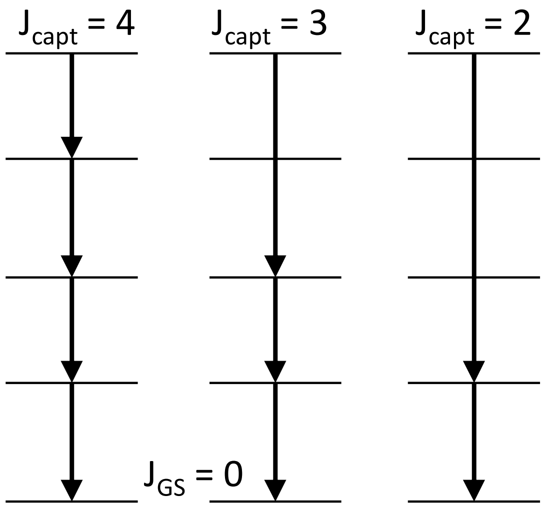
4 C_6D_6 @ n_TOF



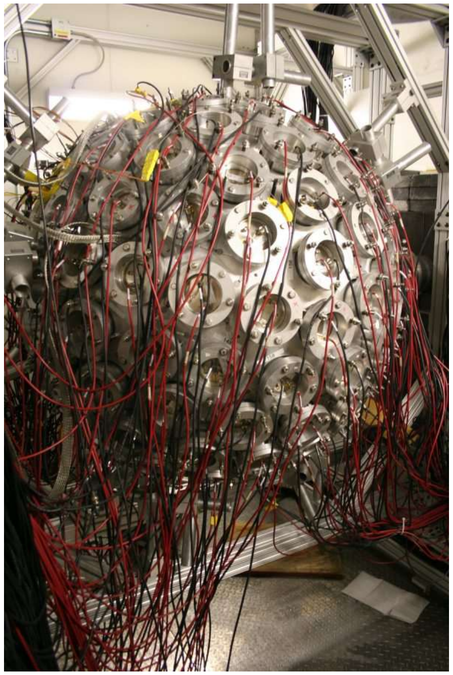
DANCE @ LANSCE



Principle of the multiplicity method



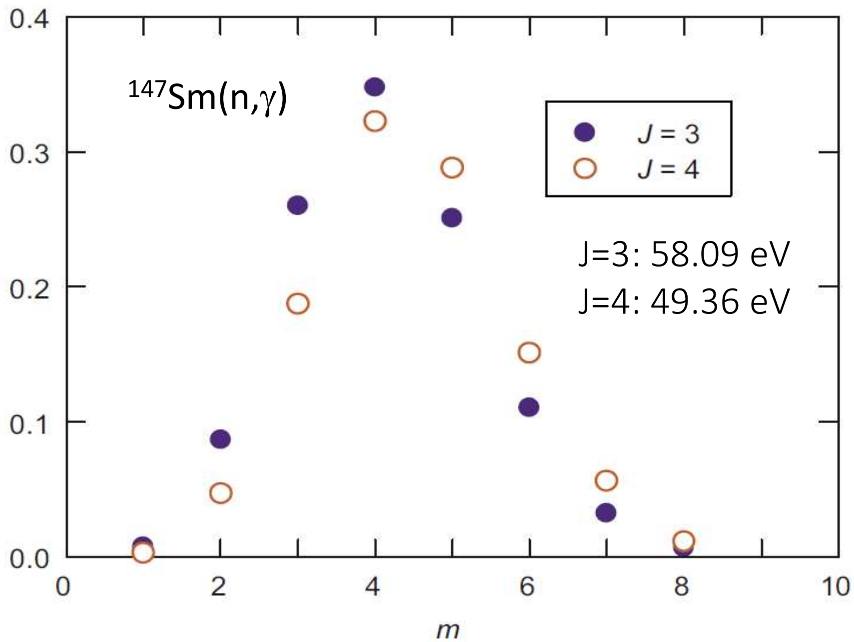
Example that corresponds to ^{95}Mo with ground state of 5/2+

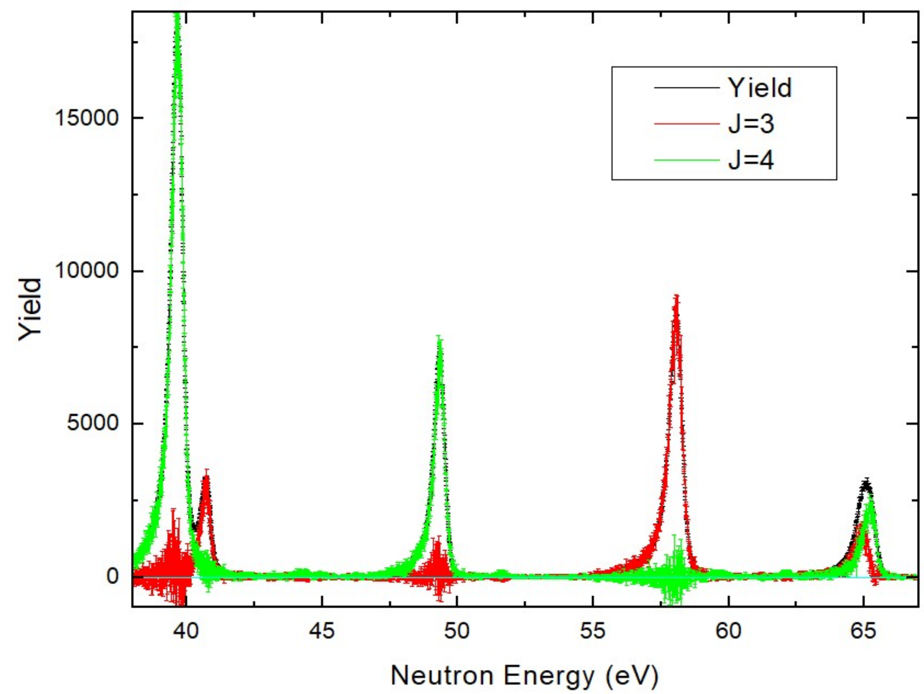


- assuming only dipole transitions ⇒ different average multiplicity (and average energy) is expected for different ΔJ
- E1 and M1 transitions have different probabilities ⇒ different average multiplicity might be expected for different parity of capturing state
- If detector allows to measure multiplicity distribution (or at least average multiplicity), data could be used
  ⇒ high-efficiency detector needed (BaF_2 balls)

Principle of multiplicity method

"Prototypical" multiplicity distributions (DANCE)





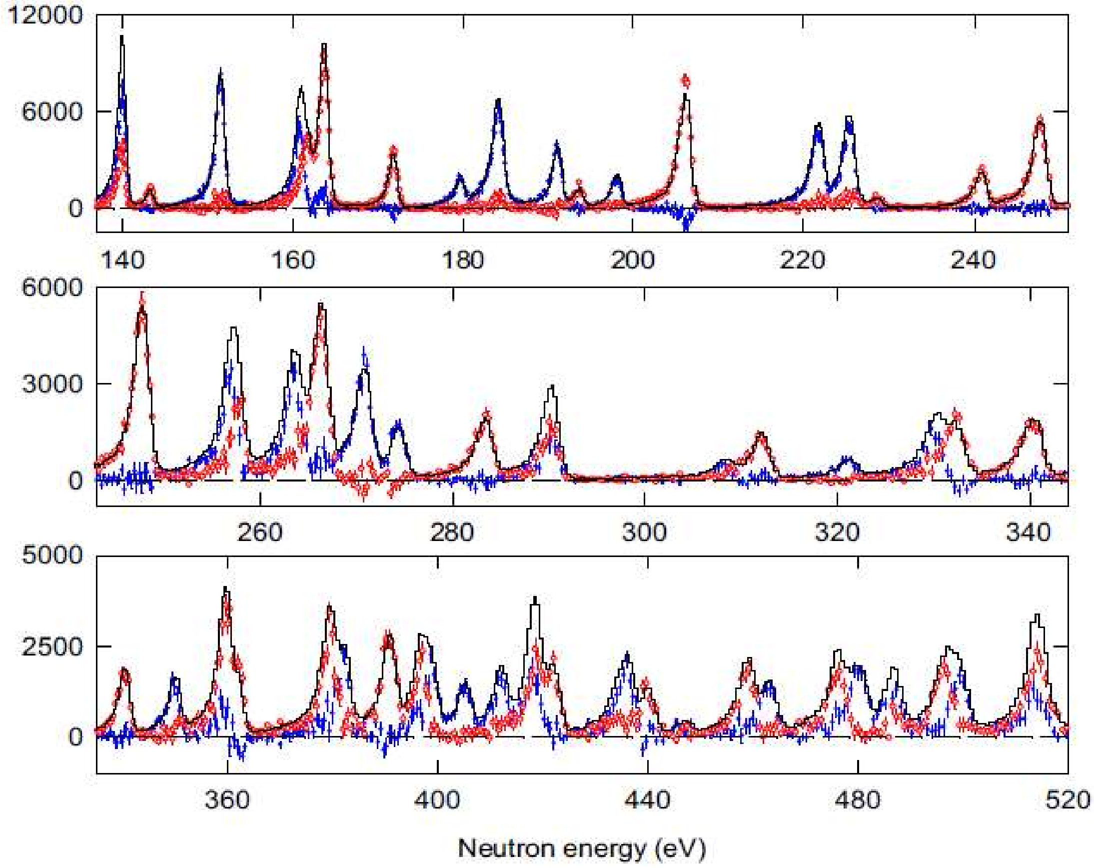
Decomposition of yield (exp y) into two (or more) "prototypes" μ_m (with contributions/yields q) using a χ^2-based minimization

- more m than number of prototypes needed

$$S^2 = \sum_m \frac{1}{\sigma_m^2}\left(y_m - \sum_{\pi=\pm} \mu_m^\pi q^\pi\right)^2$$

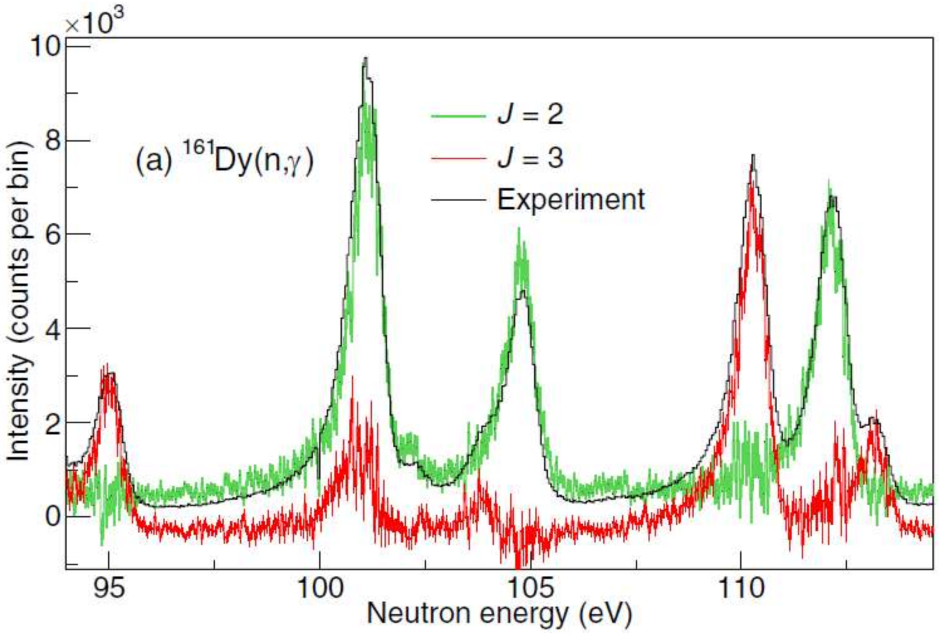
F. Becvar et al., NIMA 647 (2011) 73–85

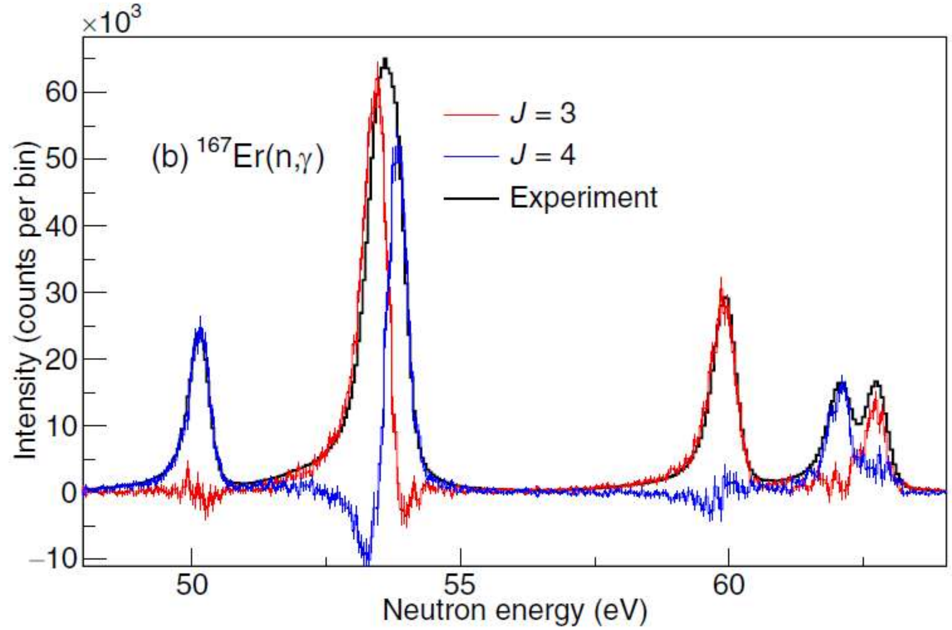
Example



F. Becvar et al., NIMA 647 (2011) 73–85

Examples

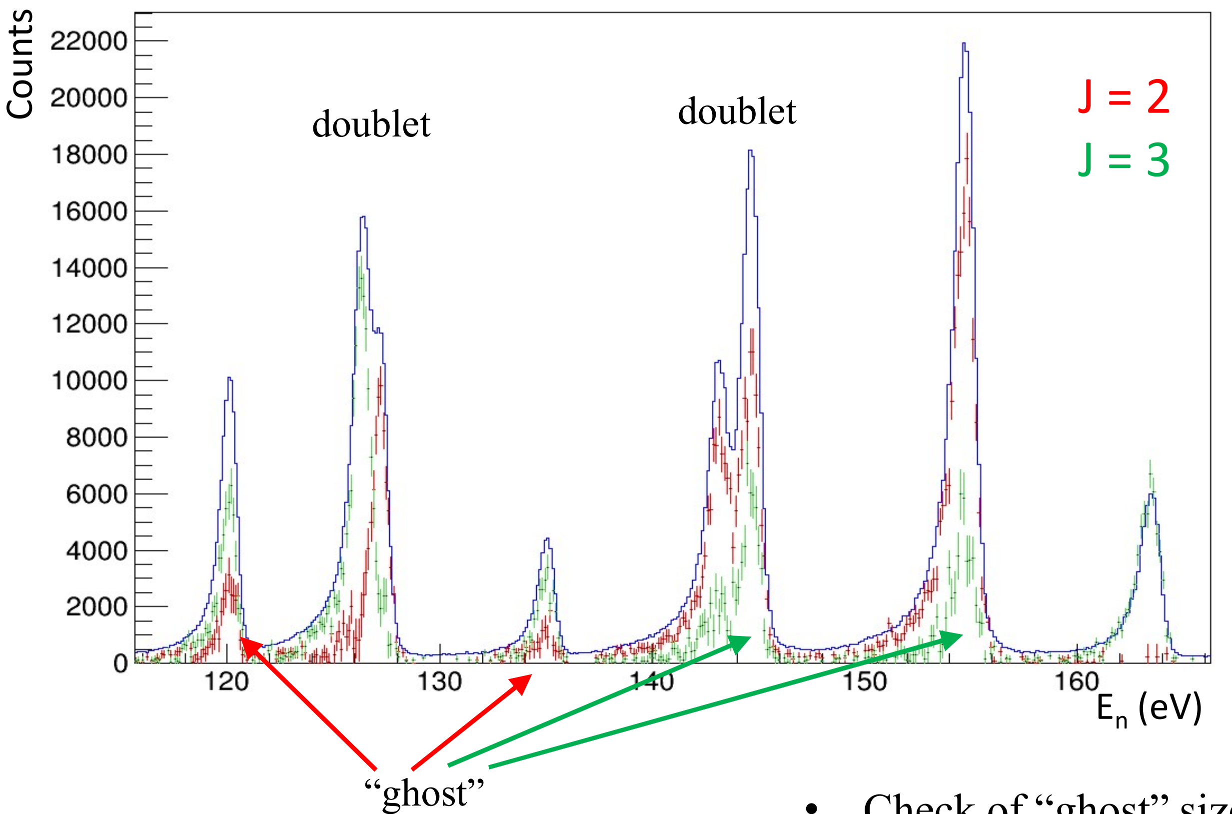




- The decompositions were performed using m = 2–6
- Previously unreported doublets near 101 eV in ^{161}Dy and 53.5 eV in ^{167}Er clearly seen
- In ^{167}Er a clear indication of a doublet presence comes already from the observed resonance shape
- The decomposed shapes nicely agree with the shapes of the neighbor resonances (resonance shape can be checked)

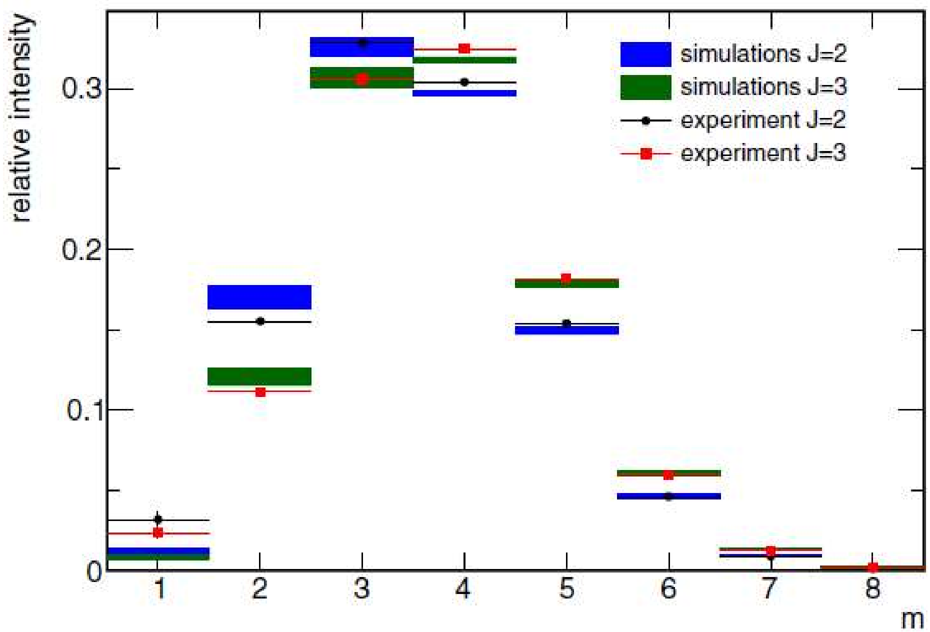
I. Knapova et al., PRC **106**, 034607 (2022)

Examples – "imperfections"



- Fluctuations lead to imperfections – presence of *ghost resonances* (other spin)
- The standard deviation of "ratio of the area of the ghost to the total area" *R*
  ~0.12 in 167Er
  ~0.09 in 161Dy
- In ^{163}Dy a couple of resonances with similar decomposed contributions for both *J*, and the standard deviation of *R* was found to be at least 0.15, but still allows spin determination for vast majority of resonances
- Check of "ghost" sizes from simulations of γ decay (DICEBOX): ~ 0.12(2) for ^{167}Er, 0.09(2) for ^{161}Dy, and 0.25(6) for ^{163}Dy (agrees with experiment)

Example – comparison with simulations

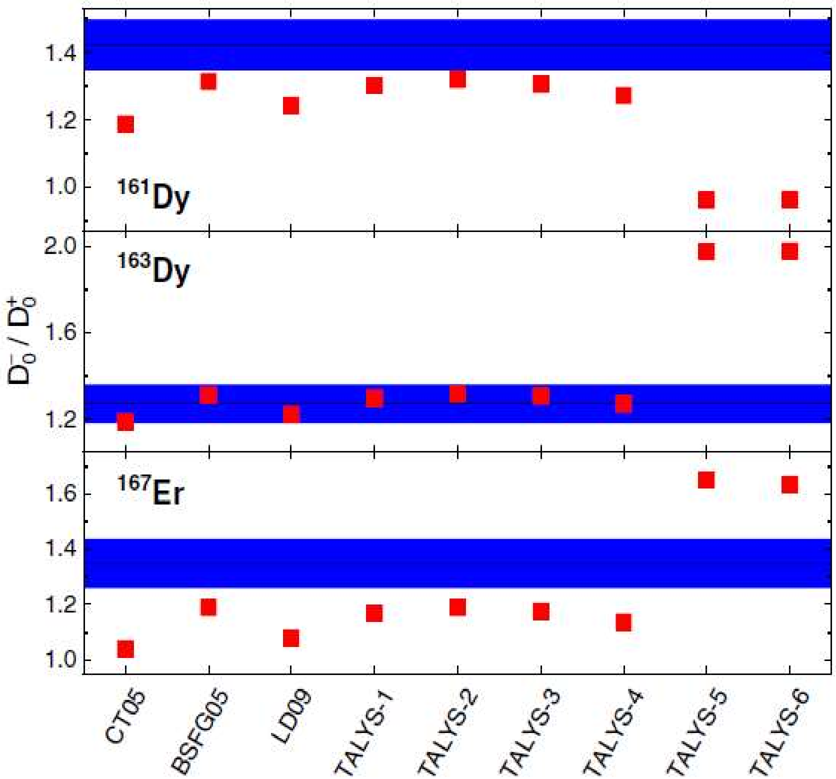


- Comparison of average experimental and simulated multiplicity distribution of ^{161}Dy resonances.

- Only events with sum energy between 7.6 and 8.4 MeV used to construct the individual resonance spectra, which are then normalized to their integral for *m*>2.
- The mean and standard deviation of distributions are calculated using the maximum likelihood fit.
- The larger spread of simulated values is due to the random nature of “nuclear supra-realizations”.

I. Knapova et al., PRC **106**, 034607 (2022)

Comparison with spin dependence of “available” NLD models



- Determination of resonance spins allows comparison of experimental data to predictions of spin dependence from different available NLD models
- Blue corridor depicts uncertainty of the experimental ratio.

Comparison with NLD models from

- TALYS1.8,
- CT05 and BSFG05 is von Egidy and Bucurescu PRC72, 044311 (2005),
- LD09 is von Egidy and Bucurescu PRC80, 054310 (2009).

Problems with the method

Unfortunately, does not work for all nuclei

- the spin difference between resonances and GS small (^{197}Au)
- fluctuations in multiplicity distribution is large within the same spin in comparison to the difference within the two spins.

- A check for each isotope needed – applicability is nucleus sensitive.
- Such a check requires knowledge of a realistic description of γ decay.

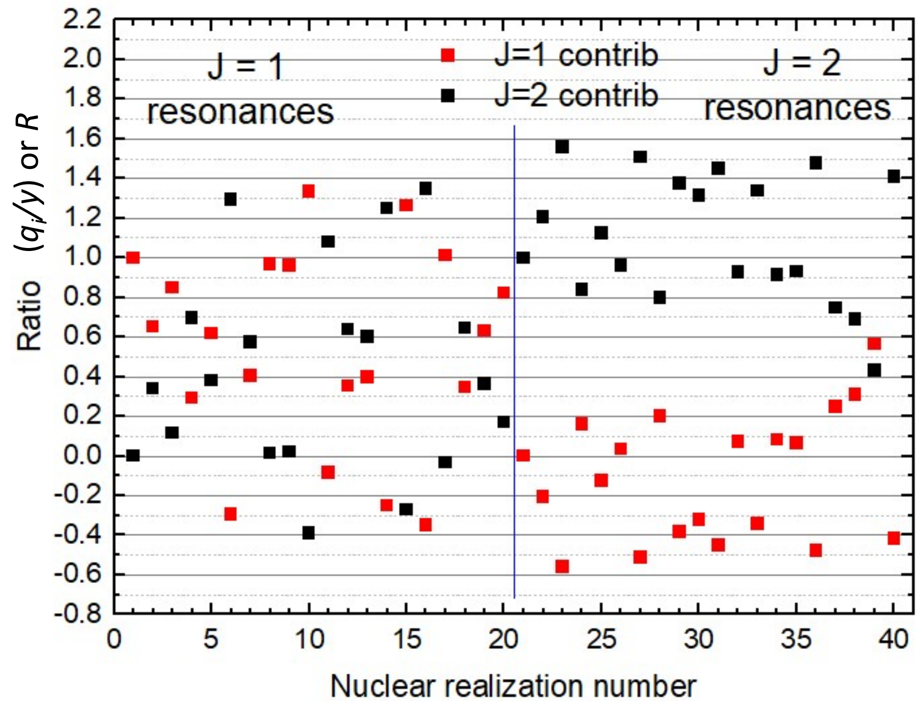
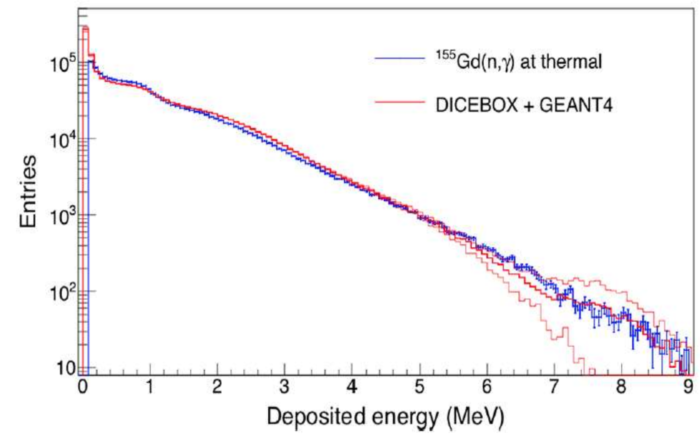


Illustration for Au
Simulated decay of resonances using DICEBOX
The same analysis as above applied to data

“Modification of the method” (P.E. Koehler, PRC 105, 054306 (2022))

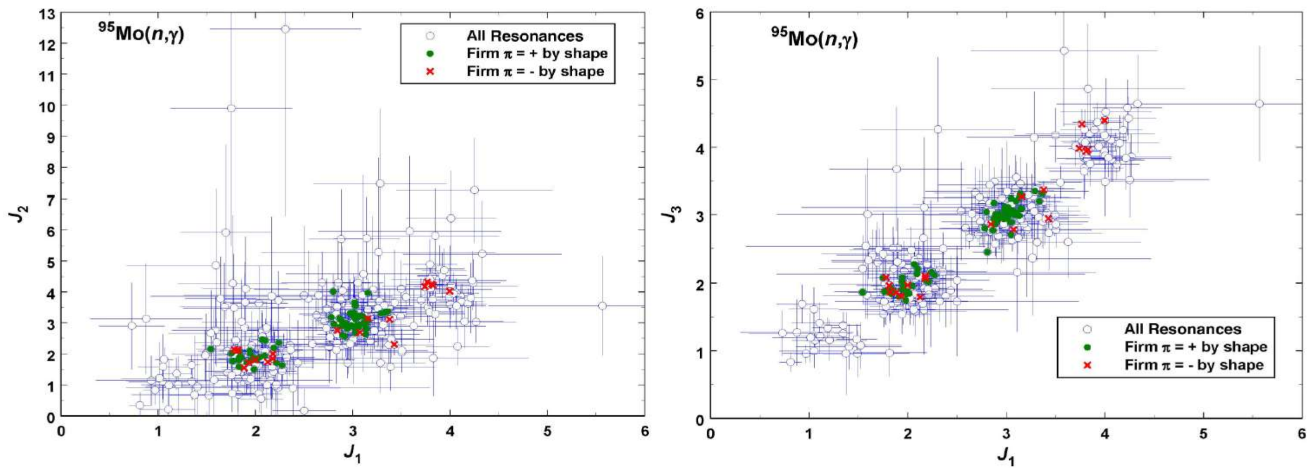
Even low-efficiency (C_6D_6) detectors can be used for γ multiplicity method (from capture exp.) despite their low-E_γ resolution if more detectors used and sufficient number of coincidences detected



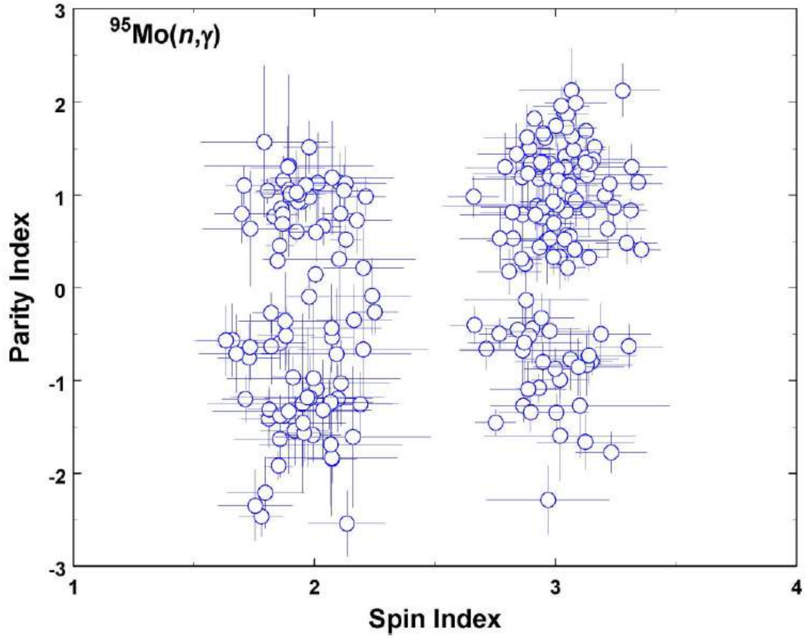
Different multiplicity distribution must impact

- the number of coincidence with respect to non-coincidence events,
- the energy distribution of emitted photons (low-deposited energy vs high-deposited energy events)

Different ratios of these quantities can be made (optimized) – these ratios are normalized to form “indexes” (“spin indexes”, “parity indexes”)

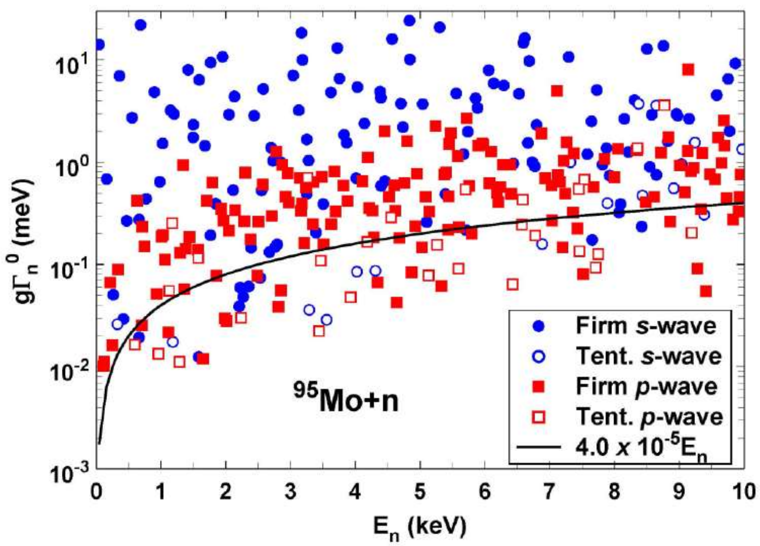


“Modification of the method” (P.E. Koehler, PRC 105, 054306 (2022))



Weighted averages of the three J indexes vs weighted averages of the three π indexes for all spin J=2 and J=3 resonances with assigned firm parity.

A linear transformation was applied to the spin index so that the groups are centered at 2 and 3. Similarly, a linear transformation was applied to the parity index so that the groups were centered at -1 and 1.



Data from ORELA … difficult to say if one can apply this for any other existing measurement

Firm spin reported for many (vast majority of observed) resonances

(Additional) Indirect methods sensitive to NLD

- Analysis of Multistep-step (or Two-step) gamma ray spectra from neutron capture (sensitive to NLD energy dependence below neutron separation energy) … about 10 nuclei

- P.E. Koehler at al., EPJ A (2022) 58:195
  Difference of Γ_γ from resonances in ^{197}Au with different spin was used to be used to say something about spin dependence of NLD below neutron separation energy … probably only one nucleus (not sure if more cases possible)

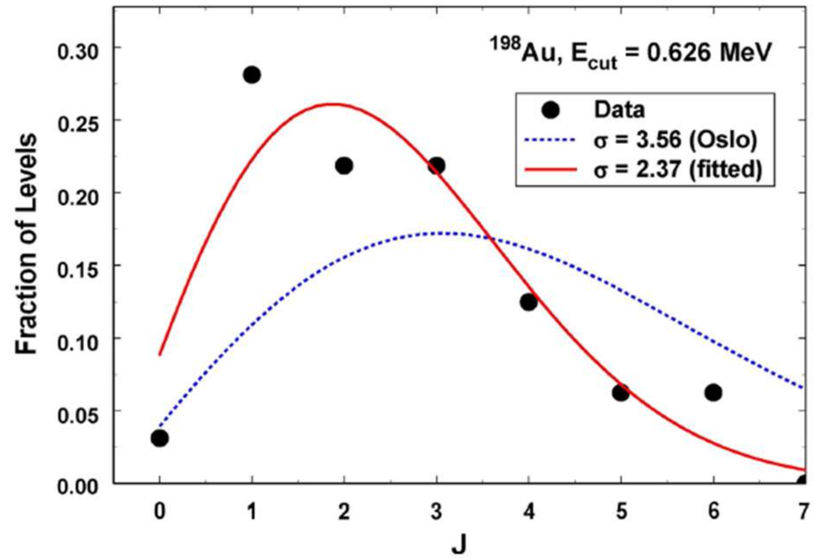


Fig. 6 Spin distribution for known levels in ^{198}Au below E_{cut} = 0.626 MeV (black circles) together with the spin distribution used in Ref. [4] (dashed blue curve) and our fit to these data using the standard formula (solid red curve)