

Statistical Evidence for Oscillatory Components in Neutron-Induced Cross Sections*

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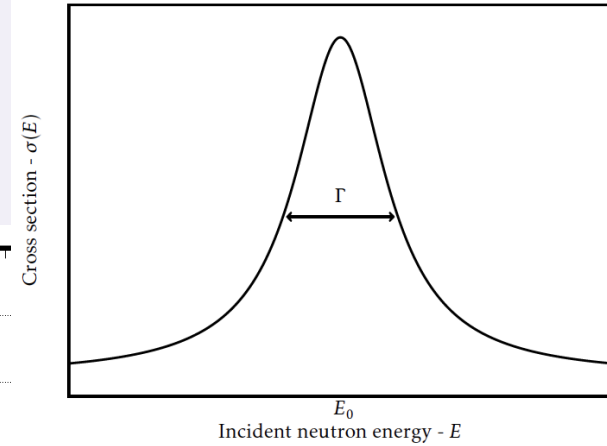
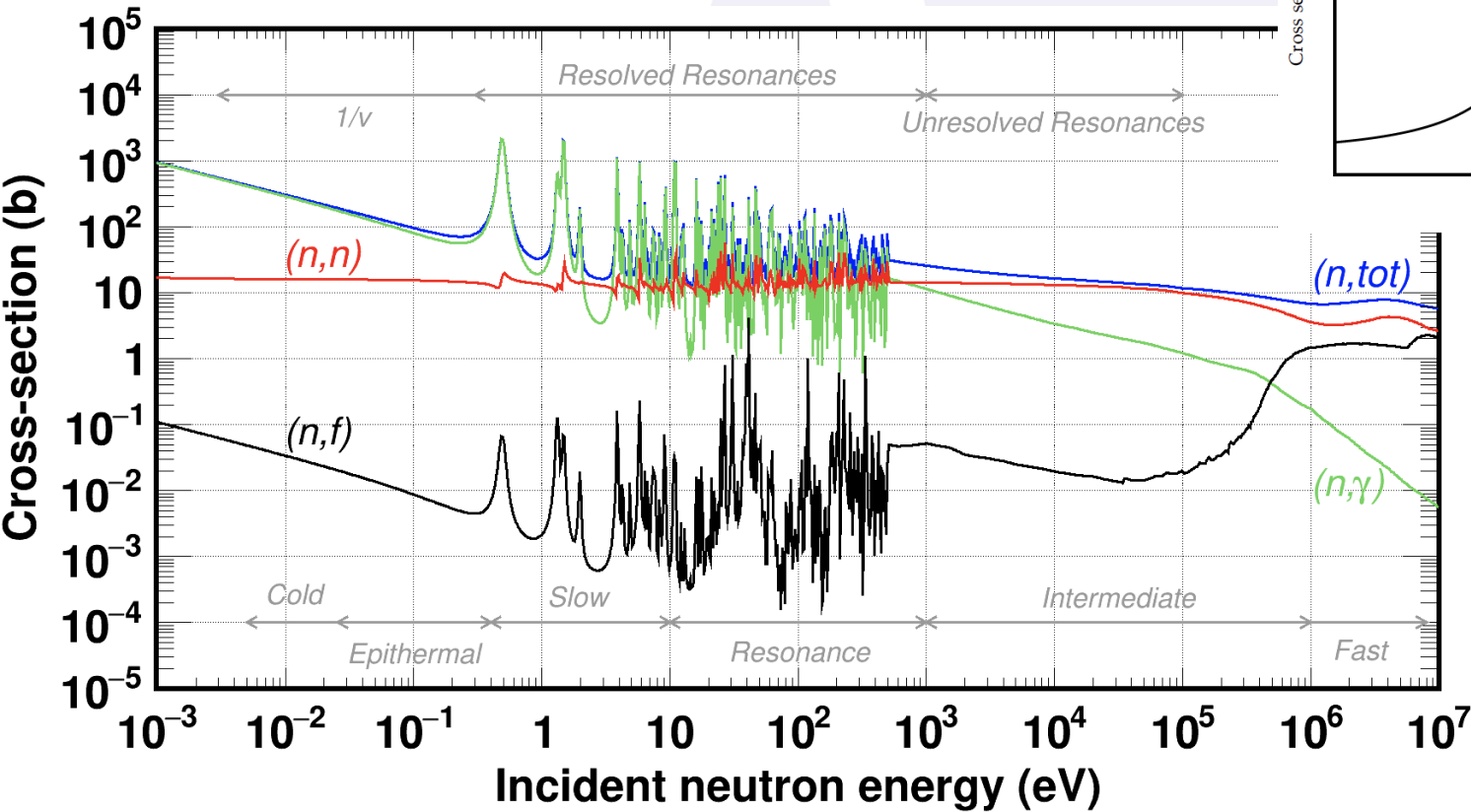
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Neutron-induced cross sections

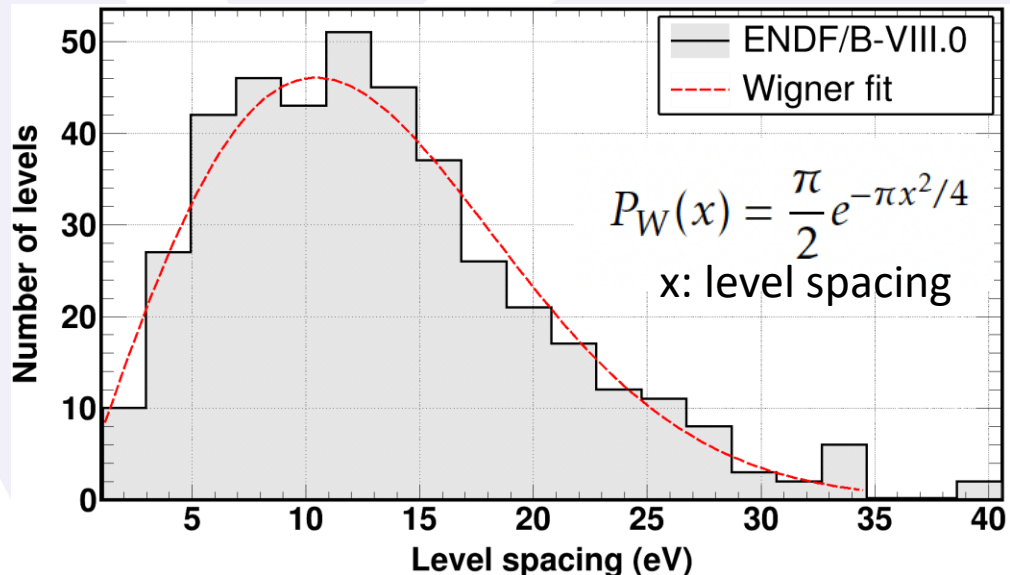
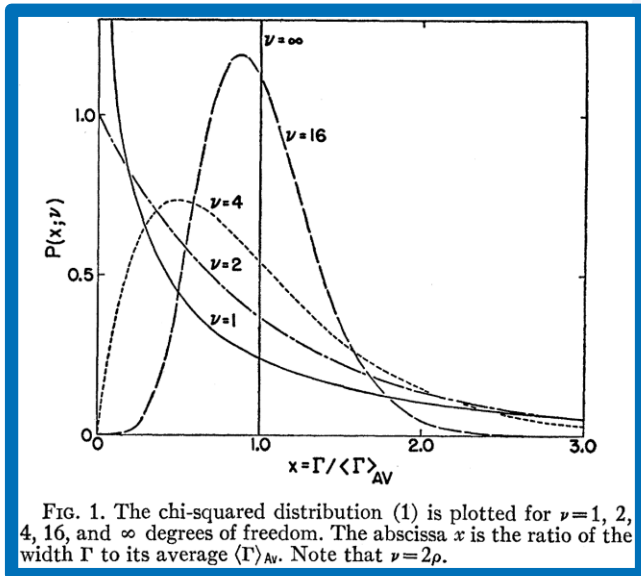
- Q-values are of the order of MeV
- **At low neutron energies, cross sections exhibit large fluctuations: resonances**
- Resonance is characterized by its mean energy (E) and reaction width (Γ ; Γ_γ for capture, Γ_n for scattering, Γ_f for fission, Γ for total, etc)



Random Matrix Theory - RMT

- Theory cannot predict the position and width of each resonance
- RMT can, however, predict:
 - **Width distributions**
 - Porter-Thomas for neutron widths (chi-square distribution with 1 degree of freedom)
 - Gamma width distributions are narrow and don't change with energy
 - Energy spacings follow the Wigner distribution
 - Widths and energies are uncorrelated
- **RMT predicts that fluctuations in cross sections are entirely random**

Phys. Rev. 104 2 (1956)



Why testing RMT is important ?

- RMT pervades the physics of virtually all complex systems*
 - Equilibrium and transport properties of disordered quantum systems, two-dimensional gravity, conformal field theory, chiral phase transition in quantum chromodynamics, nuclear resonances, ...
- RMT is “fundamental”
 - Very few assumptions
- RMT underpins the nuclear statistical model, which is used to predict cross sections that are beyond the reach of current measurement techniques for applications such as radiochemical diagnostics, nuclear energy applications, nuclear astrophysics, ...
- **Difficult to understand how RMT could be wrong: the few observed deviations from RMT (in neutron resonances) remain unexplained**

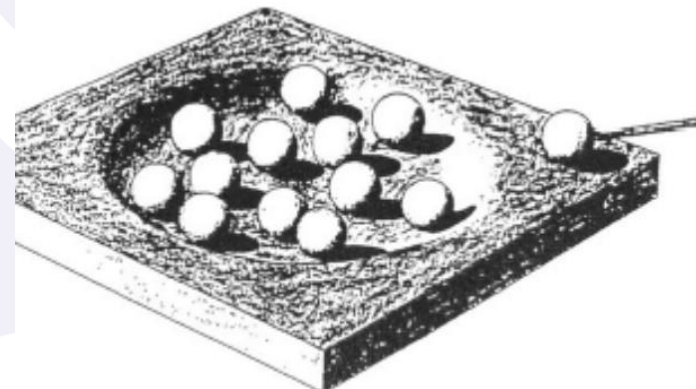
*T. Guhr et al, Phys. Reports 299, 189 (1998)

A Taste of RMT: A (Very Loose) Derivation of the Porter-Thomas Distribution (PTD)*

- The PTD is based on the following assumptions
 - The reaction is a single-channel process: Elastic scattering only and time-reversal invariance holds
 - The compound-nucleus (CN) model applies
- The matrix elements between the CN states and the incoming neutron are very complex (many many components) and essentially unrelated to each other.
- As a result, the central-limit theorem applies and hence these matrix elements are Gaussian distributed with zero mean
- Experimental Reduced widths Γ^0_n (Γ_n/\sqrt{E}) are proportional to the squares of the matrix elements, which leads to Γ^0_n having a χ^2 distribution with one degree of freedom, $\nu=1$, which is called the PTD
- **Simple assumptions**

*E. Porter and R. G. Thomas, "Fluctuations of Nuclear Reaction Widths", Phys. Rev. 104, 483 (1956)

Bohr's wooden toy model
Science 86 2225 (1937)



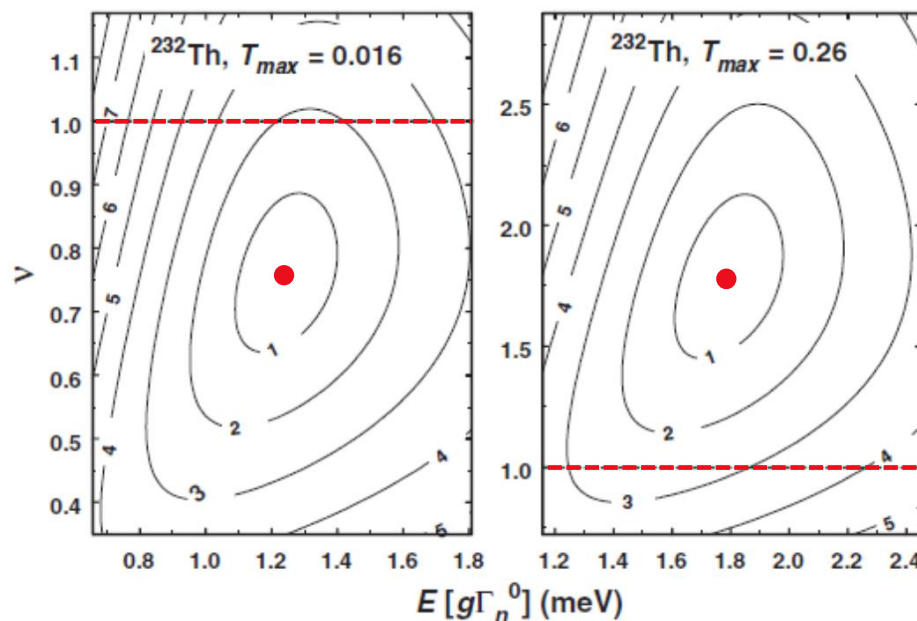
Testing RMT with Neutron Resonance Data

- Consensus is that neutron resonance data are consistent with RMT, but there are a few cases where RMT ($\nu=1$) is rejected with high confidence
 - ^{232}Th , $\nu=2$, Forman et al., Phys. Rev. Lett. 27, 117 (1971)
 - ^{232}Th , ν changes from 2 to 1 as energy increases, Rahn et al, Phys. Rev. C 6, 1854 (1972)
 - ^{147}Sm , ν changes from 1 to 2.7 (2.9σ) as energy increases, Koehler et al., Phys. Rev. C 76, 025804 (2007)
 - $^{192,4}\text{Pt}$, $\nu = 0.5$ (99.997% Confidence Level), Koehler et al., Phys. Rev. Lett. 105, 072502 (2010)
 - ^{150}Nd , $\nu = 1.93(12)$, Papst et al., Phys. Rev. Lett. 135 052501 (2025)
 - Systematic study, Koehler and Stamatopoulos, Phys. Rev. Lett. 135 112501 (2025)
 - ^{147}Sm , $\nu > 2$ (99.997% CL)/ Γ_γ distribution changes as energy increases, Amberger et al., to be submitted to Phys. Rev. Lett. and C (2026)
 - ^{149}Sm , Γ_γ distribution changes abruptly as energy increases, Stamatopoulos et al., to be submitted to Phys. Rev. Lett and C (2026)
- **Only a few investigated the validity of RTM. Interest is-hopefully-growing**

Problems Testing RMT using Neutron Resonance Data

- Precision limited by small number of resonances in resolved resonance range
 - Typical number of resonances for medium weight+ nuclei = 50-300
- Both neutron capture (Γ_γ) and total cross-section data (Γ_n, Γ) are needed
- **Requires careful resonance analysis: time-consuming**
- The most stringent tests compare neutron widths of s-wave resonances (angular momentum = 0) to the Porter-Thomas distribution (PTD)
- Requires careful corrections for missed resonances and elimination of p-wave resonances (angular momentum = 1)

Koehler, Phys. Rev. C (84) 034312 (2011)



With p-wave
Contamination

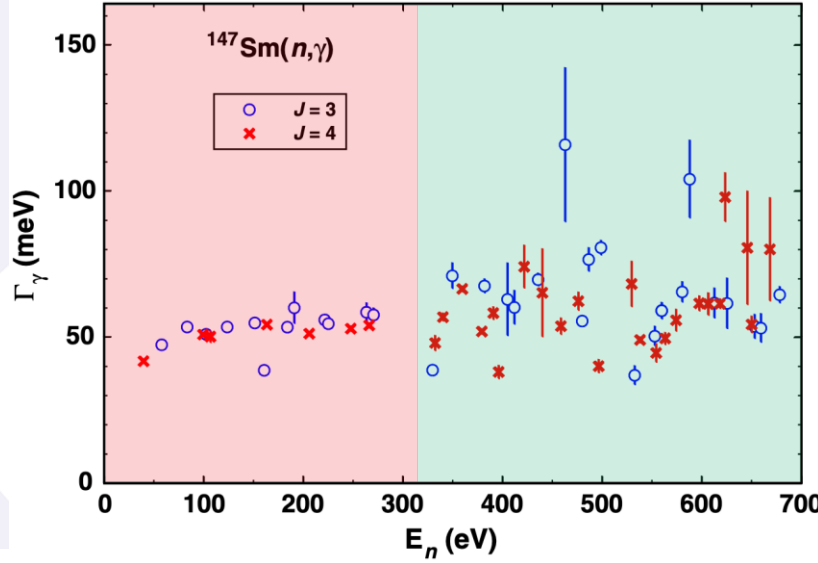
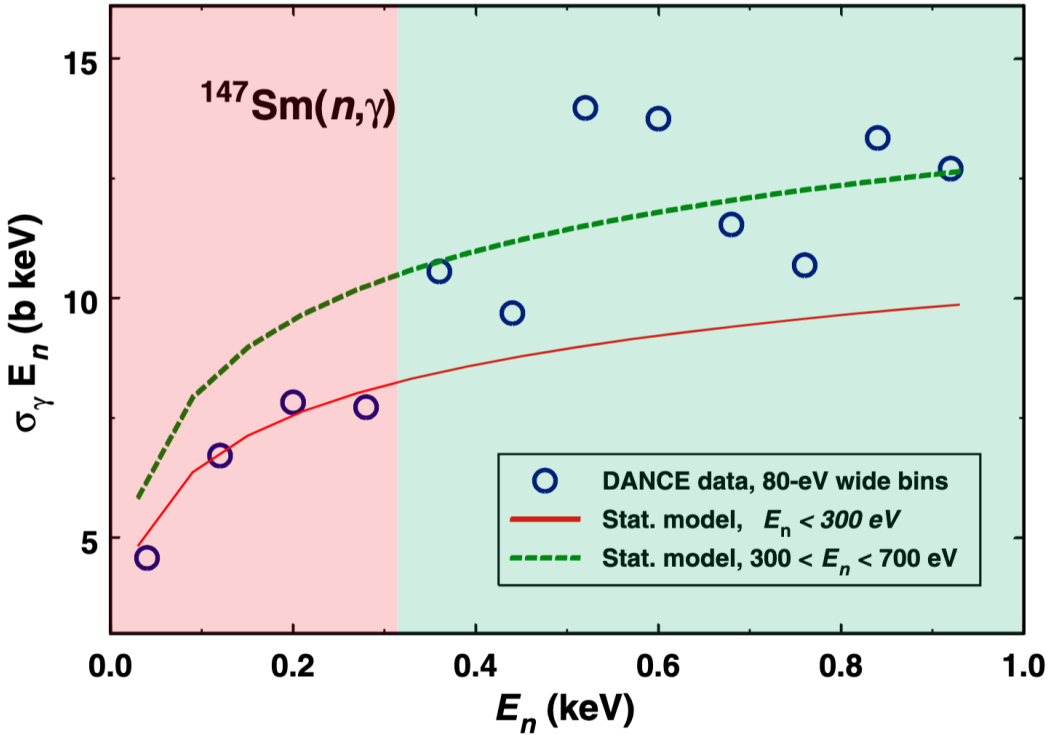
$\nu=1$ within 2σ

p-waves eliminated

$\nu=1$ within 3σ
(is it really 1 degree
of freedom?)

Can we use cross sections instead of resonances?

- In Koehler et al., Phys. Rev. Lett. 108 142502 (2012), there is a hint that the average capture cross section changes at 300 eV
- TALYS calculations with statistical properties (Level spacing – D0, Average $\langle \Gamma_\gamma \rangle$, Gamma strength function – S_0) extracted from resonance data **below** and **above** 300 eV, yield different cross sections
- An unusual cross section behavior was observed in 2012 in data where the PTD is rejected with high confidence. Coincidence?**

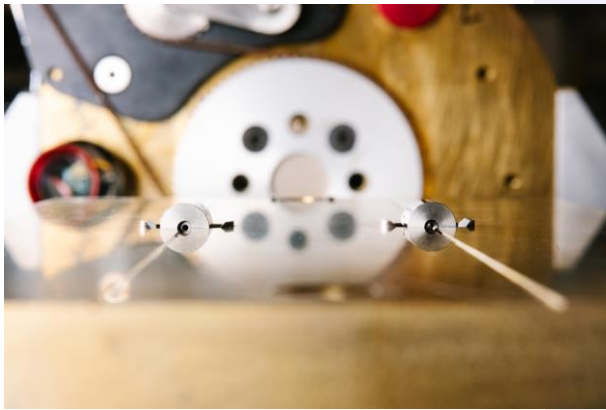


$$\langle \sigma_\gamma \rangle = \frac{2\pi^2}{k^2} \frac{S_0 \langle \Gamma_\gamma \rangle / D_0}{S_0 + \langle \Gamma_\gamma \rangle / D_0} W = f(\Gamma, \Gamma_n, D_0)$$

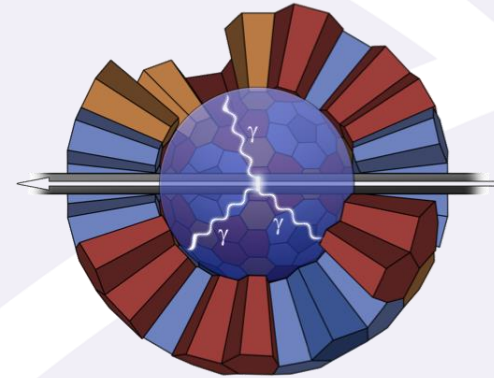
- k : Wave number
- W : Width fluctuation factor

New (n,tot) and "new-old" (n, γ) cross section data on ^{149}Sm at the Los Alamos Neutron Science Center - :LANSCCE

- (n,tot) data taken with the new **DICER** instrument (Device for Indirect Capture Experiments on Radionuclides)
- Instrument mainly developed to constrain capture rates on radionuclides, where direct measurements are impossible
- First ever binocular neutron transmission instrument: tiny samples **>0.1 mm/10s ng**



- Detector for Advanced Neutron Capture Experiments – **DANCE**
- Gamma calorimeter with 160 BaF_2 detectors



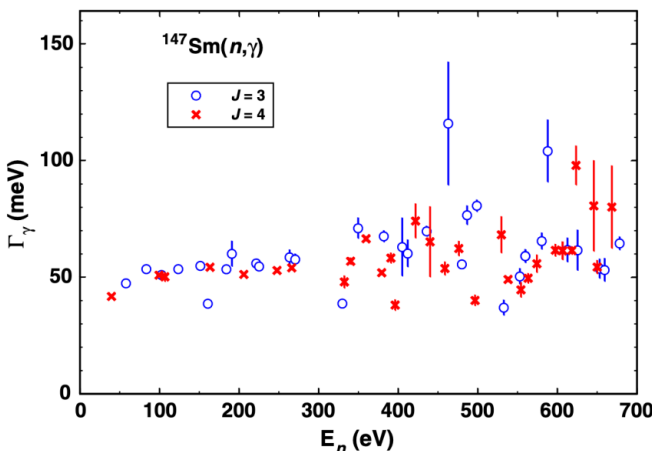
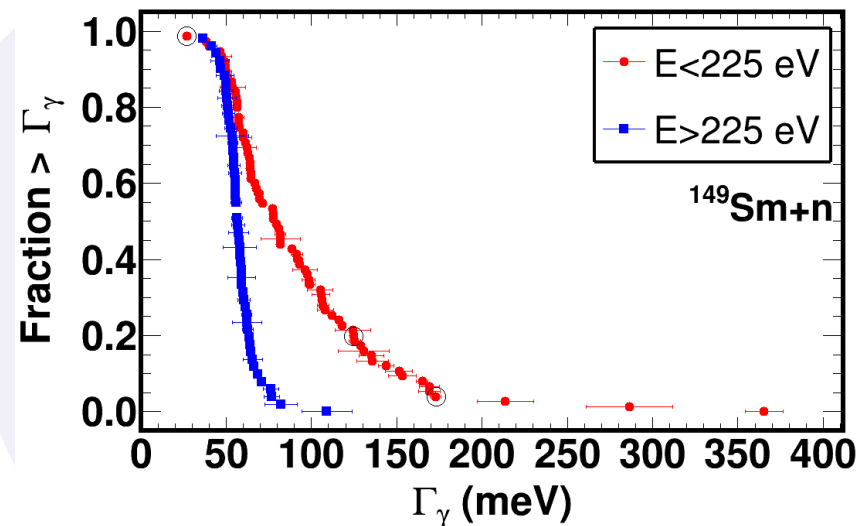
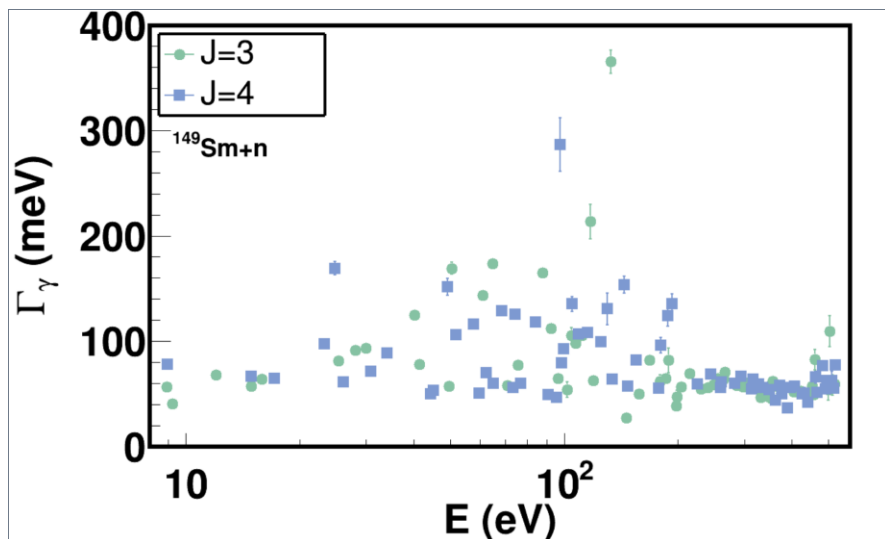
- ^{149}Sm data were taken in the early 2000s
- DANCE can extract capture cross sections and resonance spins.

- **DICER and DANCE data were analyzed, resonance parameters and cross sections were extracted.**
- **An interesting observation followed an interesting observation...**

- A. Stamatopoulos et al., NIMA (1025) 166166, 2022
- A. Stamatopoulos et al., IEEE Trans. Nucl. Science 70, (2023)
- A. Stamatopoulos et al., Neutron News 33, 12 – 14 (2022)
- A. Matyskin et al, Scientific Reports 13, 1736 (2023)
- A. Stamatopoulos et al., EPJ., Conf. 260, 03006 (2022)
- A. Stamatopoulos et al., J. Rad. Nucl. Chem. 331, (2022)
- A. Stamatopoulos et al. Phys. Rev. Lett. 134 112702 (2025)
- A. Stamatopoulos et al. Phys. Rev. C 11 034613 (2025)

Non-Statistical behavior

- Statistically significant **change in the Γ_γ distributions** around 200 eV was observed.
- Findings will be submitted for publication to Phys. Rev. Lett. (similar findings in ^{147}Sm)



Further evidence of nuclear non-statistical effects: Unexpected change in radiation width distributions of ^{149}Sm

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Phys. Rev. Lett.

Combined study of $^{149}\text{Sm}+n$ with DANCE and DICER at LANSCE

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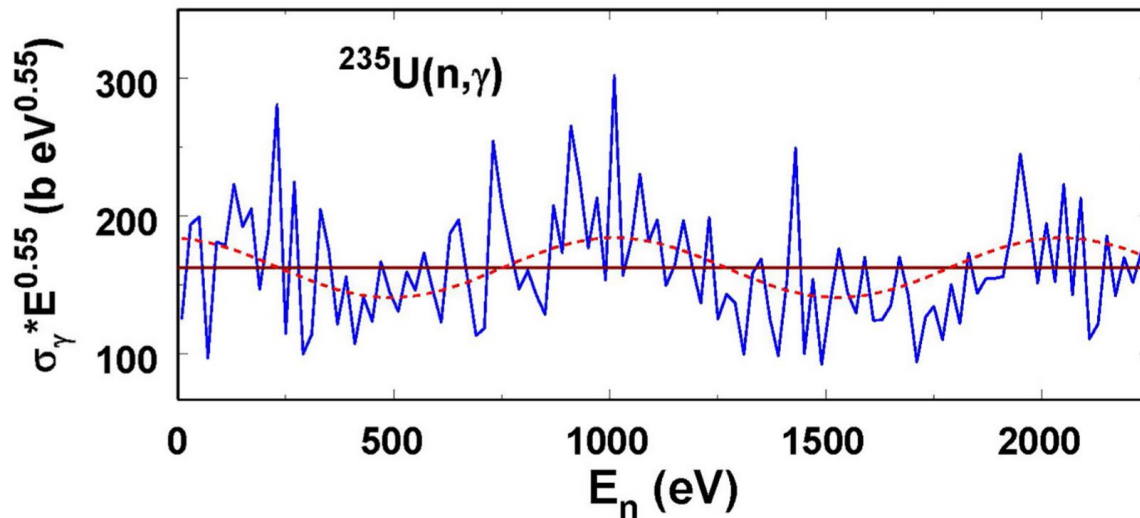
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Phys. Rev. C

Non-Statistical behavior - more

- Sm work gave rise to an interesting observation
- Neutron-capture cross sections are exhibiting a statistically significant **oscillating behavior**



PHYSICAL REVIEW LETTERS **135**, 112501 (2025)

Evidence of Oscillating Neutron-Capture Cross Sections

P. E. Koehler^{id} and A. Stamatopoulos^{id}

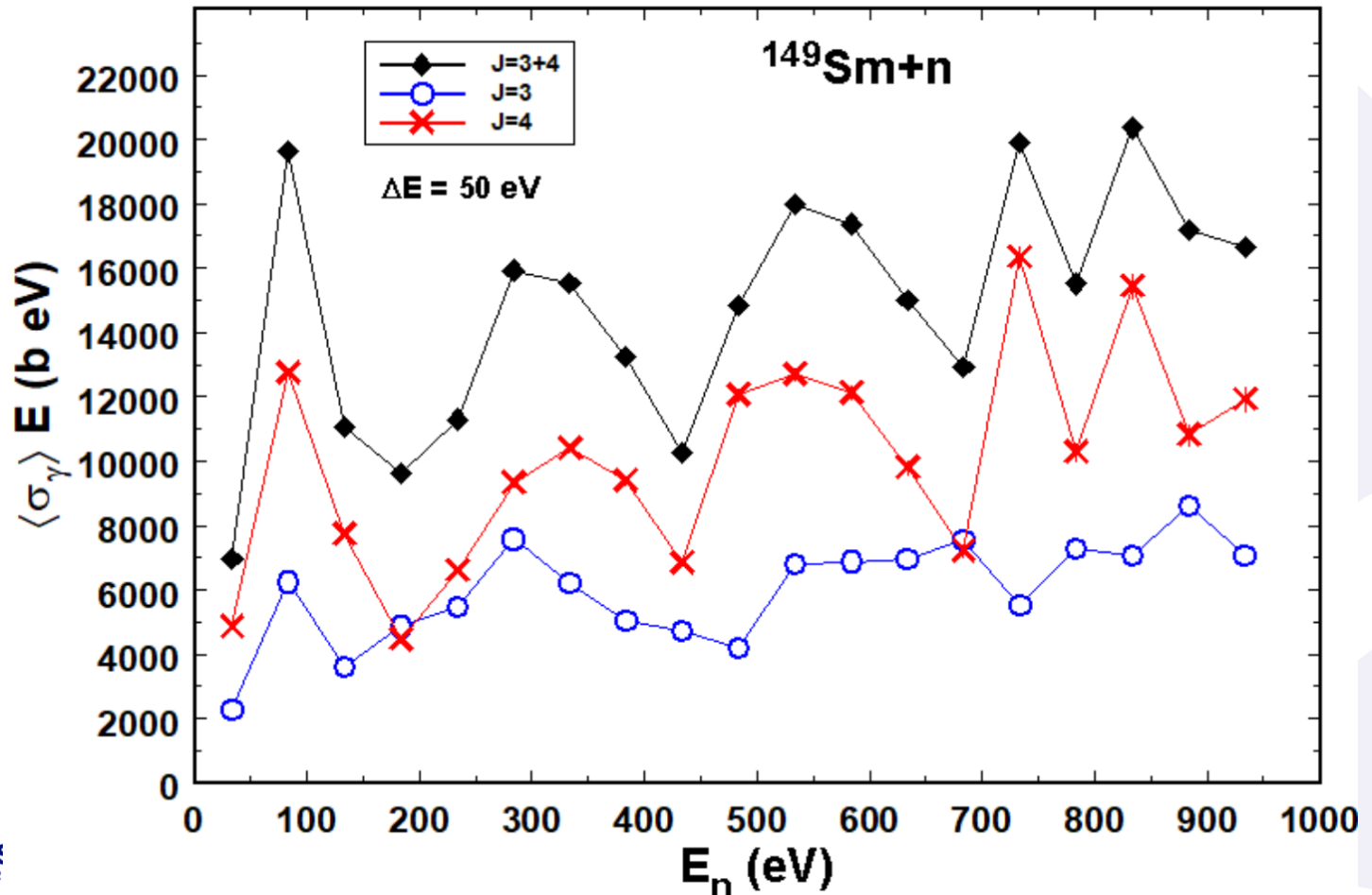
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Non-statistical behavior - More

- The average capture cross section, if binned coarsely enough to smooth resonances (i.e. $10 \times D_0$, D_0 = level spacing i.e. the average distance between consecutive resonances), exhibits oscillations
- Are they statistically significant?



Chasing significance

1. Remove long-range correlation by multiplying by E^x
2. Average over $10xD_0$ bins to equalize resolution
3. Calculate autocorrelation (A): Think of it as a Fourier transformation when there aren't enough periods in the "signal"

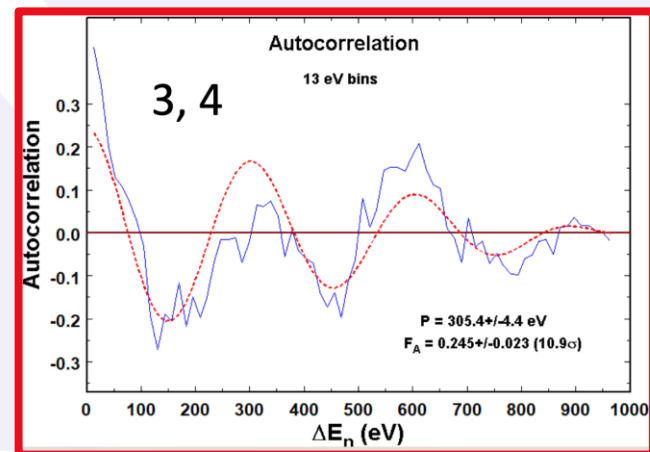
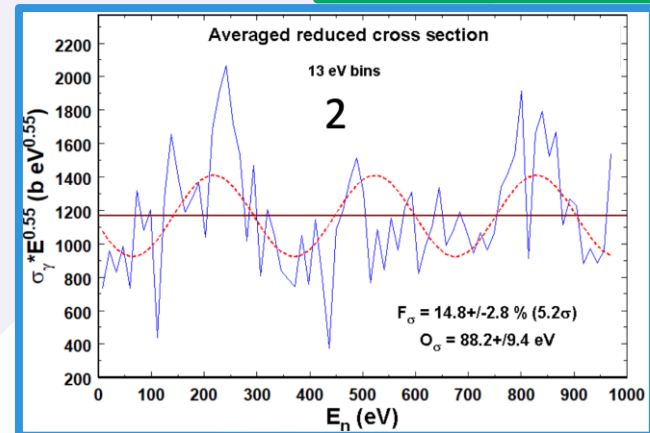
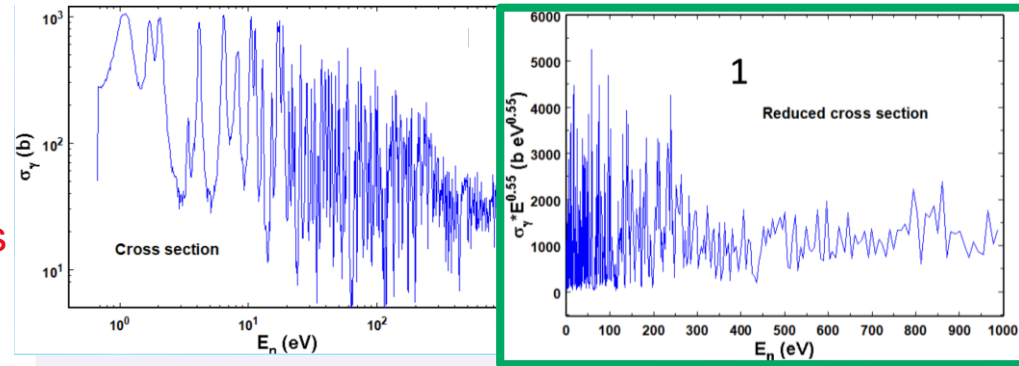
$$A_k = \frac{\sum_{i=1}^{N-k} (\sigma_i - \langle \sigma \rangle)(\sigma_{i+k} - \langle \sigma \rangle)}{\sum_{i=1}^N (\sigma_i - \langle \sigma \rangle)^2}$$

N : total bins, σ_i : cross section in bin i , k is the lag (1 to $N - 1$), $\langle \sigma \rangle$: average cross section over the entire range, $\Delta E = k \times 10D_0$

4. Fit to A for cosine to determine statistical significance of oscillations and extract period

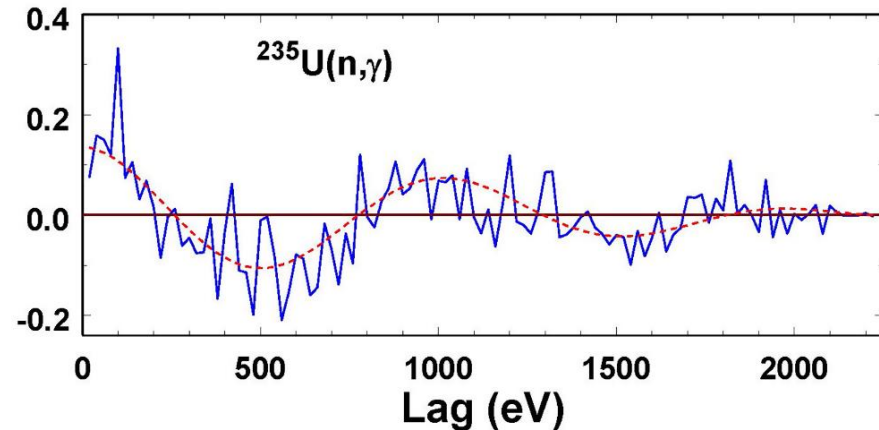
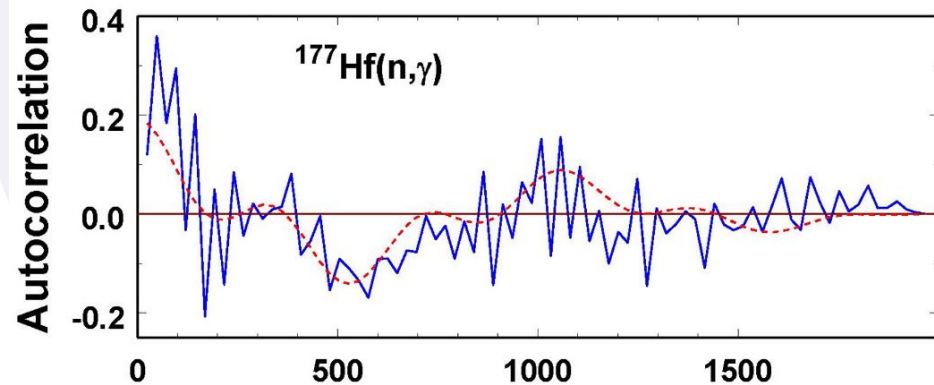
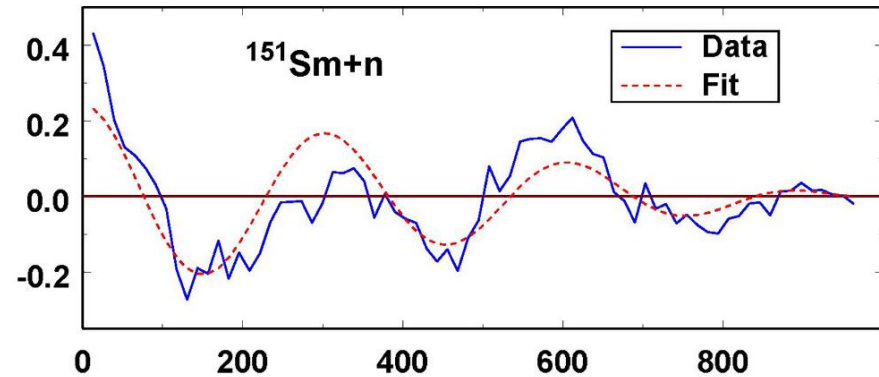
$$A_{fit}(F_A, P) = F_A \cos(2\pi\Delta E/P) (1 - \Delta E/E_m)$$

F_A is a normalization factor, P is the period, ΔE is the lag energy, and E_m the maximum lag energy



Results

1. Performed the analysis in many cross sections (either evaluations or literature data)
2. Restricted to $D_0 < 8$ eV to discern periods as short as ~ 100 eV (30 cases)
3. 9 cases not analyzed because energy range of data was too short (21 left)
4. Three cases, ($^{147,149}\text{Sm}$ and ^{177}Hf), required 2 periods to obtain accurate fits
5. Highly significant deviations from RMT are widespread
 1. $F_A > 3.2\sigma$ (99.9% sig. level) in 18 cases
 2. $F_A > 5\sigma$ in 9 cases
6. Periods range from 68.2 to 2380 eV



And then what?

1. F_A is difficult to relate to a physically meaningful quantity.
2. Can we find the fraction of the cross section due the oscillation i.e. how much the reduce cross section oscillates around an average value

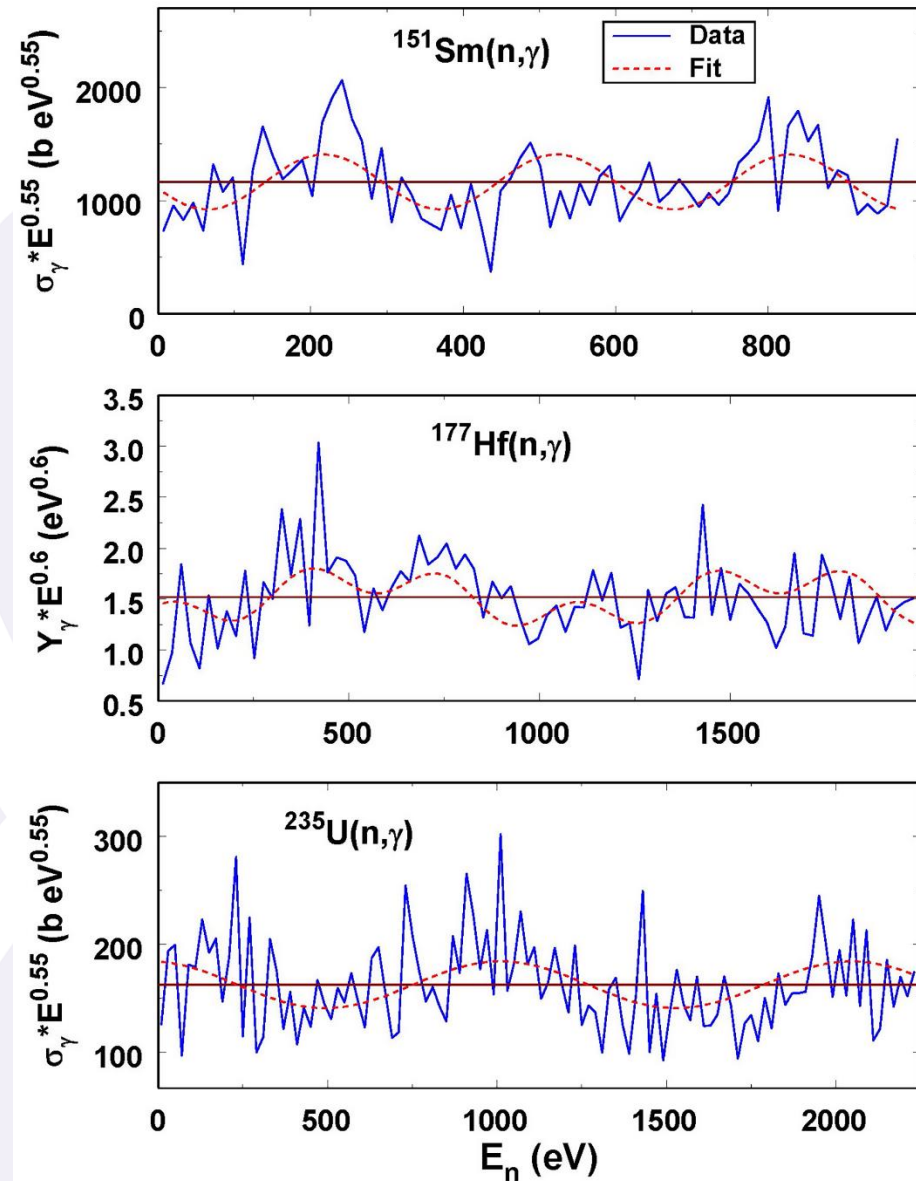
$$\sigma_{\text{fit}}(F_\sigma, O_\sigma) = \frac{\sqrt{2}\langle\sigma\rangle F_\sigma}{100} \cos\left(2\pi\left(\frac{E_n + O_\sigma}{P}\right)\right) + \langle\sigma\rangle$$

F_σ is the rms percentage of the average reduced cross section due to oscillations,

E_n the neutron energy

O_σ the cosine offset or phase,

P the period determined by fitting A in the previous step



And then what?

1. F_σ is practically the % of the oscillation around the average value
2. It seems that this is a “constant” fraction and period independent
3. Spoiler alert: There seems to be a correlation between fissile/non-fissile nuclei and perhaps deformation has something to do.
4. Currently there is no explanation as to why it happens. As of recently we are exploring a multi-well potential for n-induced reactions (fission background helps)

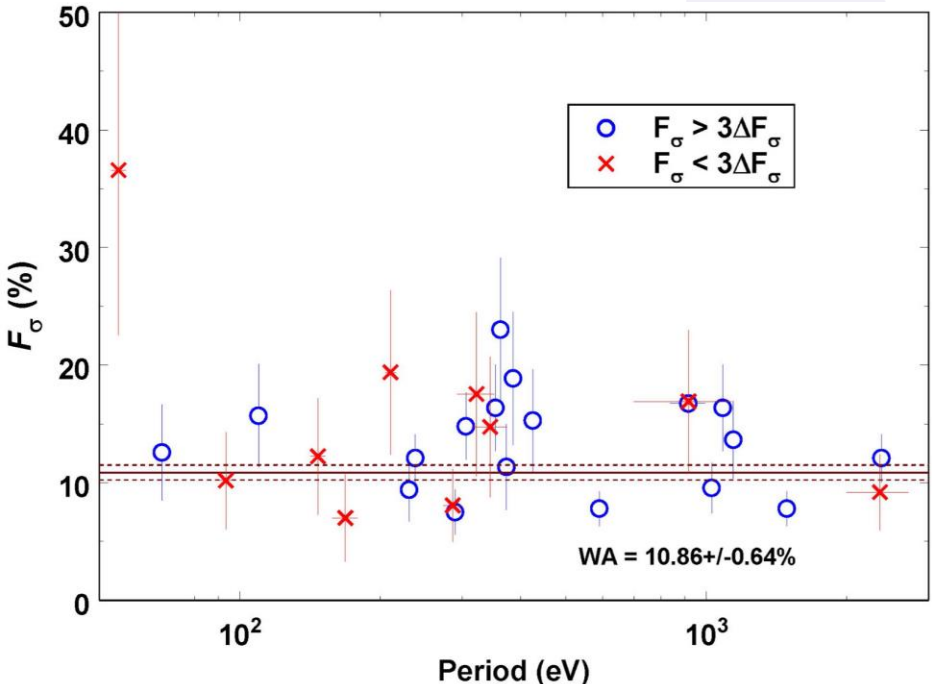
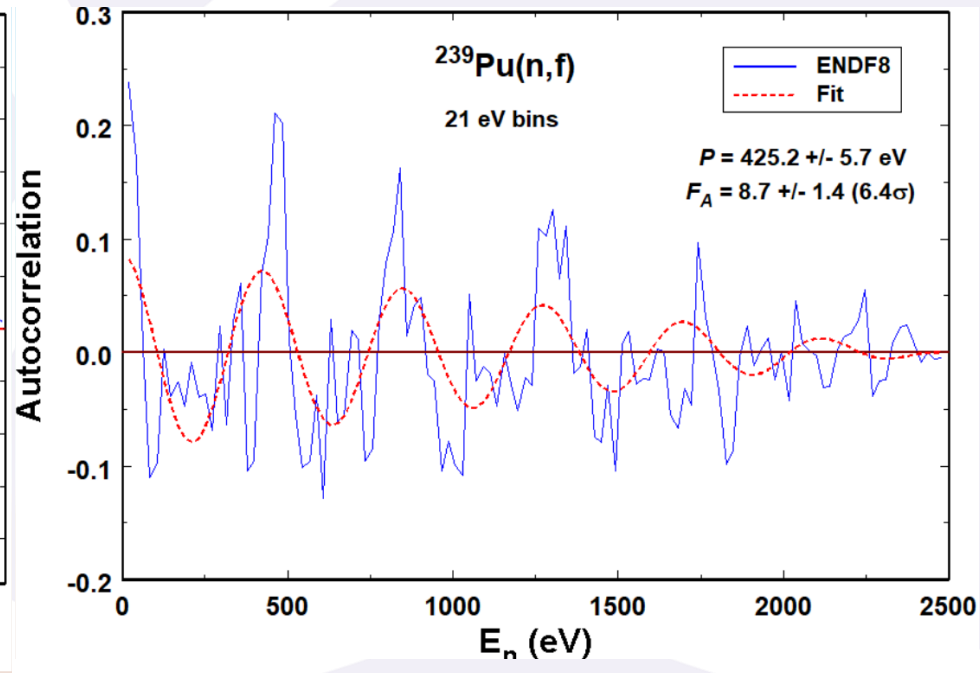
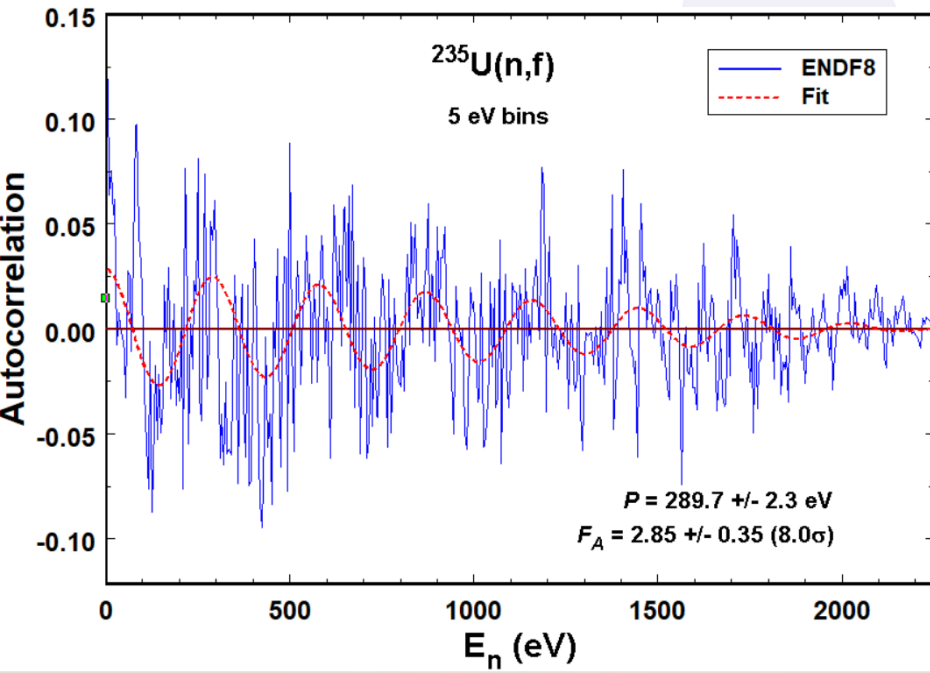


TABLE I. Results from oscillation analysis with $10D_0$ bins.

Nuclide	Ref.	E_m (keV)	ΔE (eV)	x	P (eV)	F_A (%)	F_σ (%)	O_σ (eV)
¹⁴⁷ Sm	[9]	10.0	57	0.80	$590.1 \pm 4.3, 1488 \pm 16$	$4.1 \pm 1.0, 7.1 \pm 1.0$	7.8 ± 1.5	$126 \pm 27, 898 \pm 57$
¹⁴⁹ Sm	[15]	3.0	22	0.80	$238.0 \pm 1.2, 2400 \pm 110$	$9.2 \pm 1.2, 9.9 \pm 1.2$	12.1 ± 2.0	$168.0 \pm 9.0, 810 \pm 100$
¹⁵¹ Sm	[16]	1.0	13	0.55	305.4 ± 4.4	24.5 ± 2.3	14.8 ± 2.8	88.2 ± 9.4
¹⁵⁵ Gd	[17]	1.0	18	0.60	109.76 ± 0.88	15.3 ± 2.2	15.7 ± 4.4	88.6 ± 4.9
¹⁵⁷ Gd	[17]	1.0	45	0.65	322 ± 29	12.5 ± 7.2	17.5 ± 7.0	200 ± 20
¹⁵⁹ Tb	[14]	1.195	40	0.60	916 ± 80	23.3 ± 5.2	16.7 ± 5.3	433 ± 38
¹⁶¹ Dy	[14]	0.996	22	0.65	147.2 ± 5.4	7.7 ± 3.8	12.2 ± 4.9	121.6 ± 9.6
¹⁶⁵ Ho	[14]	1.24	42	0.75	920 ± 220	11.8 ± 7.4	16.9 ± 6.1	504 ± 48
¹⁶⁹ Tm	[14]	1.9	73	0.80	362.2 ± 6.9	30.4 ± 6.2	23.3 ± 6.1	80 ± 15
¹⁷¹ Yb	[14]	1.7	61	0.80	386 ± 12	22.1 ± 6.0	18.9 ± 5.6	185 ± 18
¹⁷⁶ Lu	[18]	1.0	16	0.60	168 ± 10	3.3 ± 2.4	7.0 ± 3.7	91 ± 14
¹⁷⁷ Hf	[19]	2.0	24	0.60	$353.7 \pm 9.7, 1086 \pm 51$	$6.9 \pm 2.1, 12.5 \pm 2.1$	16.4 ± 3.7	$317 \pm 20, 546 \pm 48$
¹⁷⁹ Hf	[19]	2.0	41	0.60	230.9 ± 2.2	18.2 ± 2.9	9.4 ± 2.7	65 ± 10
¹⁸⁷ Os	[14]	1.0	46	0.80	210.5 ± 5.4	22.4 ± 5.4	19.4 ± 7.0	44 ± 12
¹⁹¹ Ir	[20]	1.0	17	0.55	286 ± 13	8.0 ± 2.5	8.1 ± 3.1	122 ± 17
¹⁹³ Ir	[20]	1.0	40	0.55	344 ± 30	15.5 ± 7.6	14.7 ± 5.9	296 ± 24
²³³ U	[21]	2.0	5	0.55	1144 ± 35	4.32 ± 0.46	13.6 ± 3.3	369 ± 48
²³⁵ U	[14]	2.0	5	0.55	1027 ± 20	4.29 ± 0.37	9.6 ± 2.1	18 ± 37
²³⁷ Np	[14]	0.5	6	0.60	68.2 ± 1.1	7.7 ± 1.8	12.6 ± 4.1	32.3 ± 3.5
²³⁹ Pu	[14]	2.5	21	0.60	373.1 ± 5.6	6.3 ± 1.3	11.3 ± 3.6	140 ± 19
²⁴¹ Pu	[14]	0.3	9	0.60	55.0 ± 2.0	11.4 ± 4.5	36 ± 14	35.3 ± 3.3
					Fission			
²³³ U	[21]	0.6	5	0.55	93.4 ± 3.1	3.1 ± 1.3	10.2 ± 4.1	77.5 ± 6.2
²³⁵ U	[14]	2.25	5	0.55	289.7 ± 2.3	2.85 ± 0.35	7.5 ± 1.9	60 ± 12
²³⁹ Pu	[14]	2.5	21	0.65	425.2 ± 5.7	8.7 ± 1.4	15.3 ± 4.4	315 ± 20
					Larger D_0			
²³² Th	[14]	4.0	158	0.65	2360 ± 360	15.2 ± 7.8	9.2 ± 3.2	2300 ± 140

What about fission?

1. Oscillations highly significant for ^{235}U (8.0σ) and ^{239}Pu (6.4σ) fission
2. Fission periods different from capture periods
3. Oscillations questionable for $^{234}\text{U}(n,f)$ (2.4σ) and $^{232}\text{Th}(n,\gamma)$ (2.0σ)



Are we the first to observe it?

1. No other known reports of oscillating neutron capture or fission cross sections
2. Autocorrelation function analysis of $^{235}\text{U}(n,f)$, G. F. Bertsch, D. Brown, and E. D. Davis, Phys. Rev. C 98, 014611 (2018)

Energy intervals analyzed were much too small to observe oscillations with periods on the order of 100 eV as seen in the present work

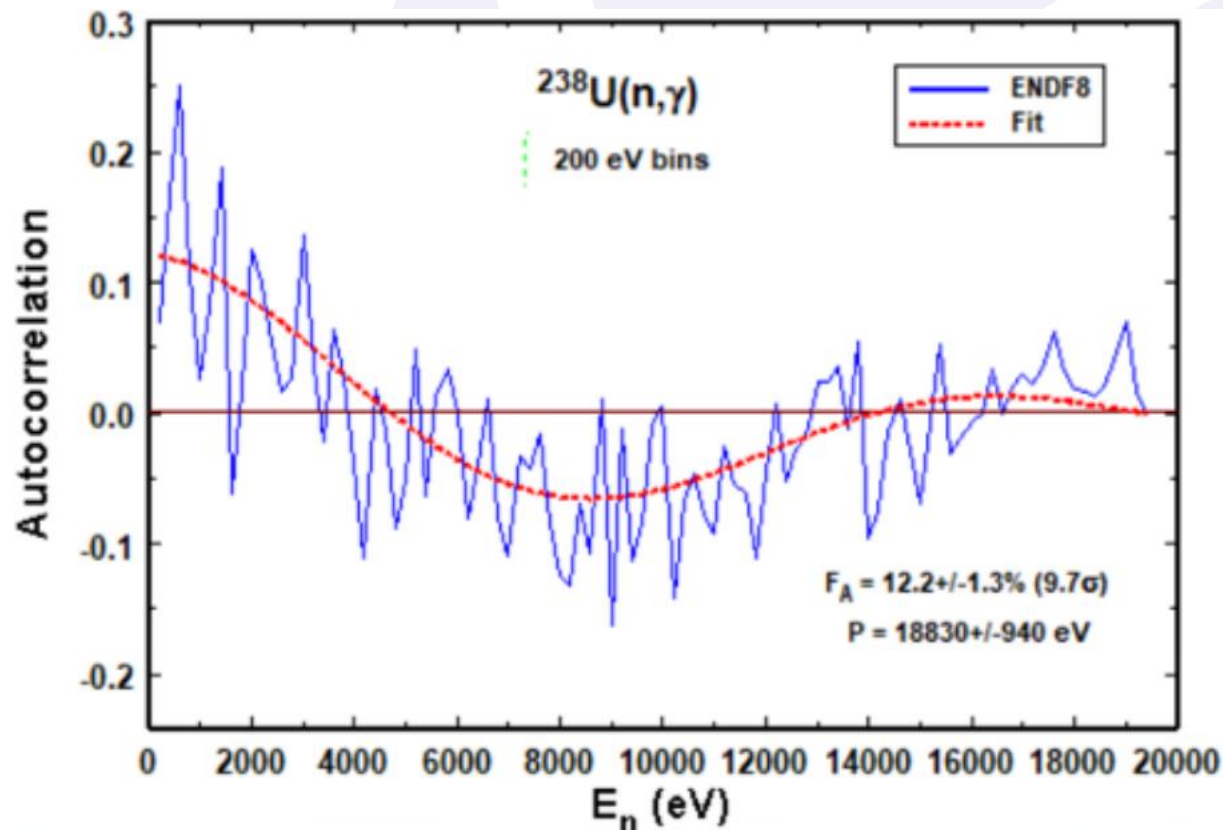
3. Some works on (n,tot) cross section in 10s MeV range: Ramsauer effect.
Developed theory does not apply at the low energies of the present work
Theory predictions do not agree with present data
 1. J. M. Peterson, Phys. Rev. 125, 955 (1962)
 2. I. Angeli and J. Csikai, Nucl. Phys. A158, 389 (1970)

Does it matter?

1. Greatly expands the number of highly significant deviations from RMT
2. Oscillations are common: Of the 22 neutron-capture plus 3 neutron fission cross sections analyzed, 10 (15) exhibit oscillations at the 5σ (3σ) level or greater
3. Suggests that there is something missing from the theory of neutron capture and fission reactions in the resolved resonance range
4. Could oscillations impact criticality calculations?
235U and 239Pu(n, γ) and (n,f) cross sections have highly significant oscillations
Oscillations are an autocovariance
Is this autocovariance information preserved in cross-section processing for criticality applications?

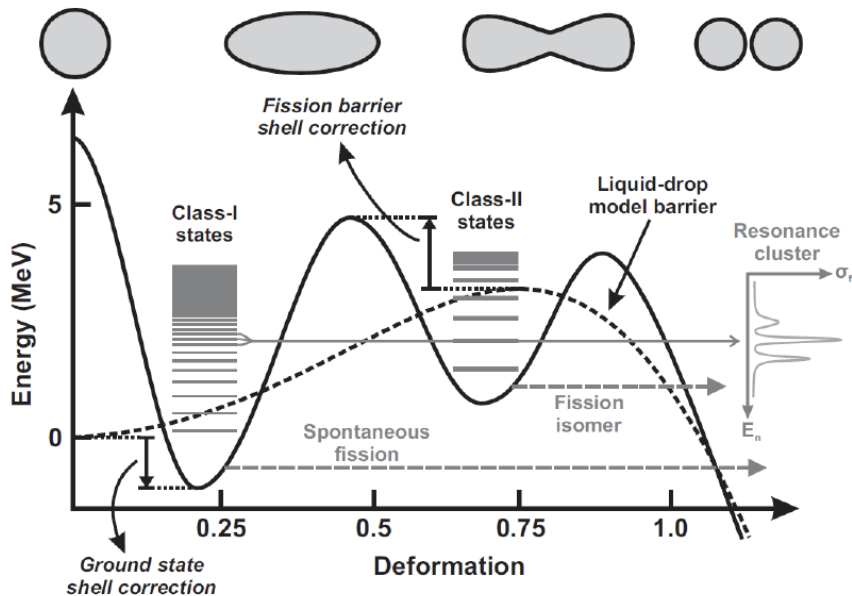
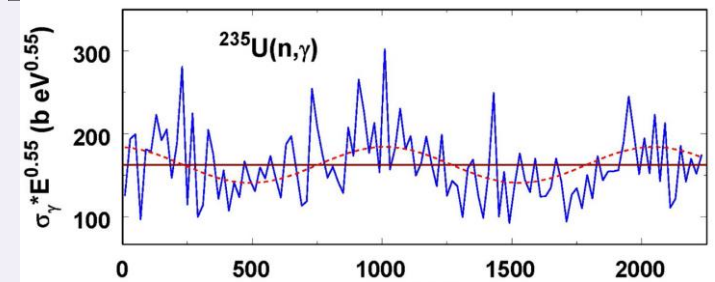
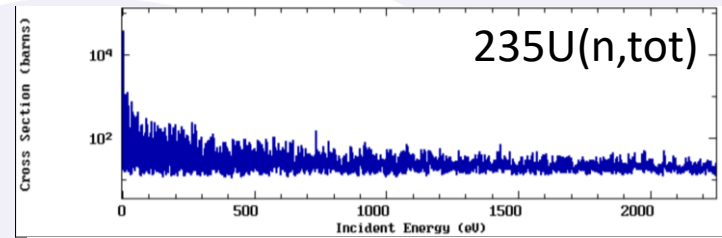
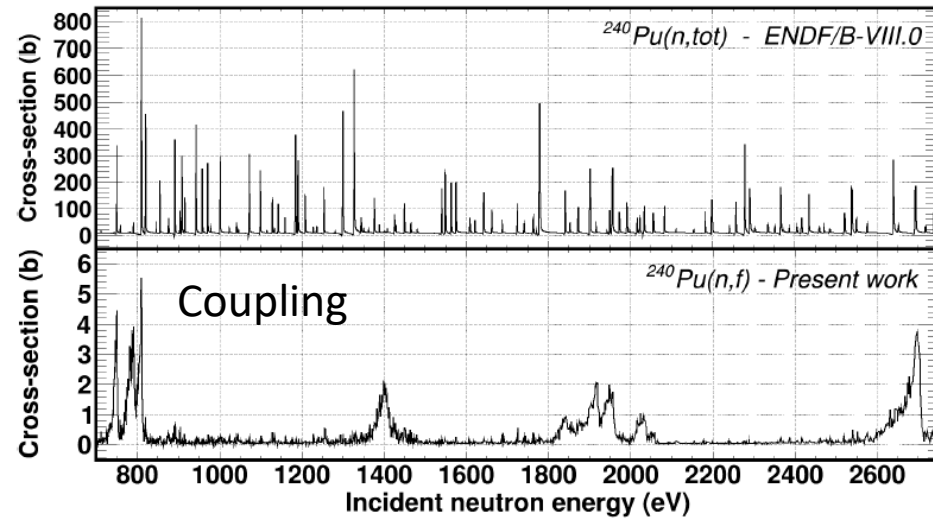
What's next?

1. Need neutron-capture data for 9 nuclides with $D_0 < 8$ eV: $^{151,153}\text{Eu}$, ^{163}Dy , $^{173,175}\text{Lu}$, ^{181}Ta , ^{189}Os , ^{229}Th , and ^{231}Pa
2. Search for oscillations in neutron resonance parameters? Might shed light on what's causing oscillations. Parameters of sufficient quality are lacking in most cases.
3. Apply technique to more nuclides with larger D_0 . Larger lower limit on period that can be detected.



What's next?

1. Is there any physics related to it ?
2. Reminds me of coupling between Class-I and Class-II states in fission



The team



Paul Koehler



Thanos Stamatopoulos

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NUCLEAR CRITICALITY SAFETY PROGRAM
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**Thank you for your
attention!**



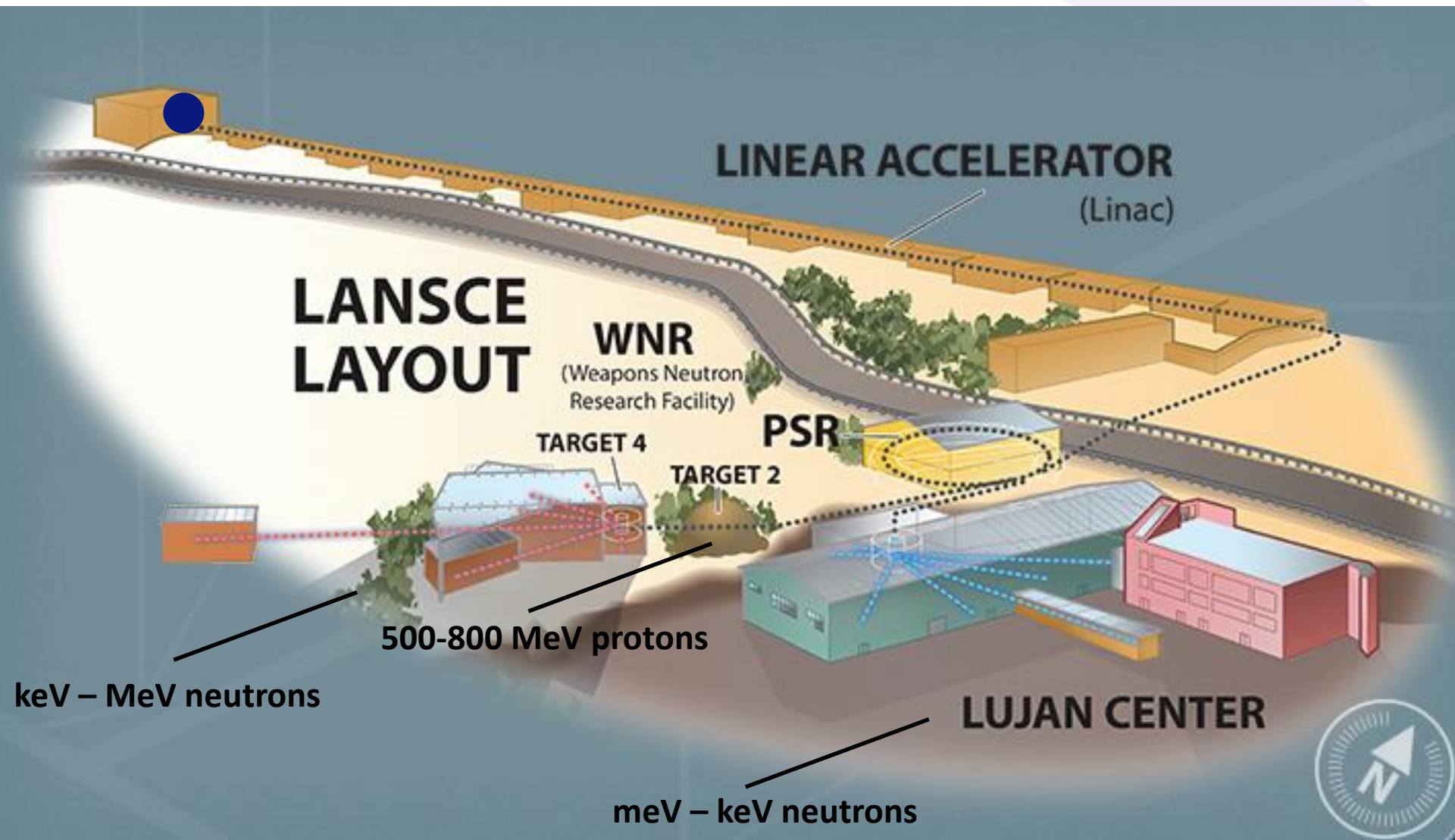
Back-up slides



The Los Alamos Neutron Science Center

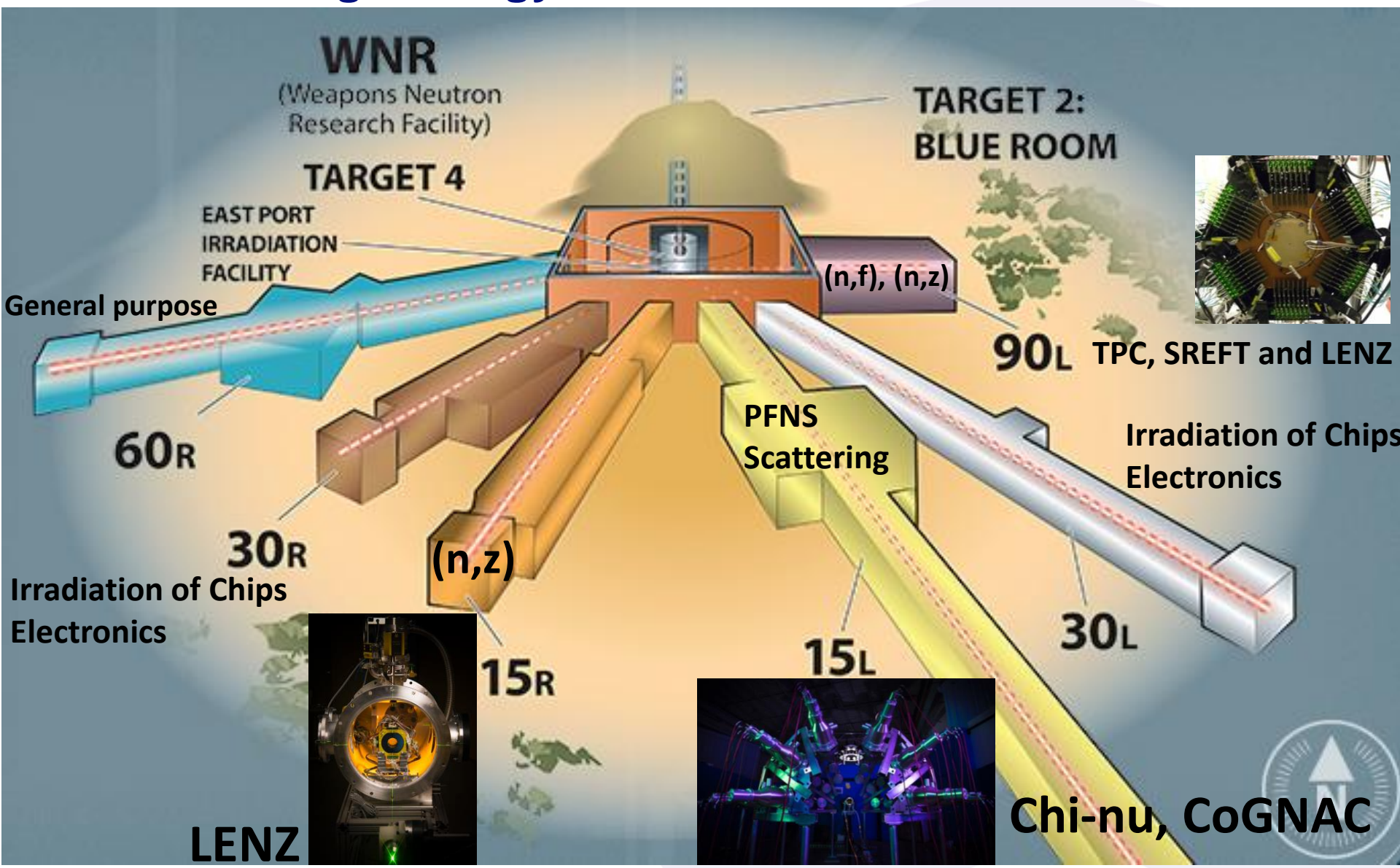


The Los Alamos Neutron Science Center - LANSCE



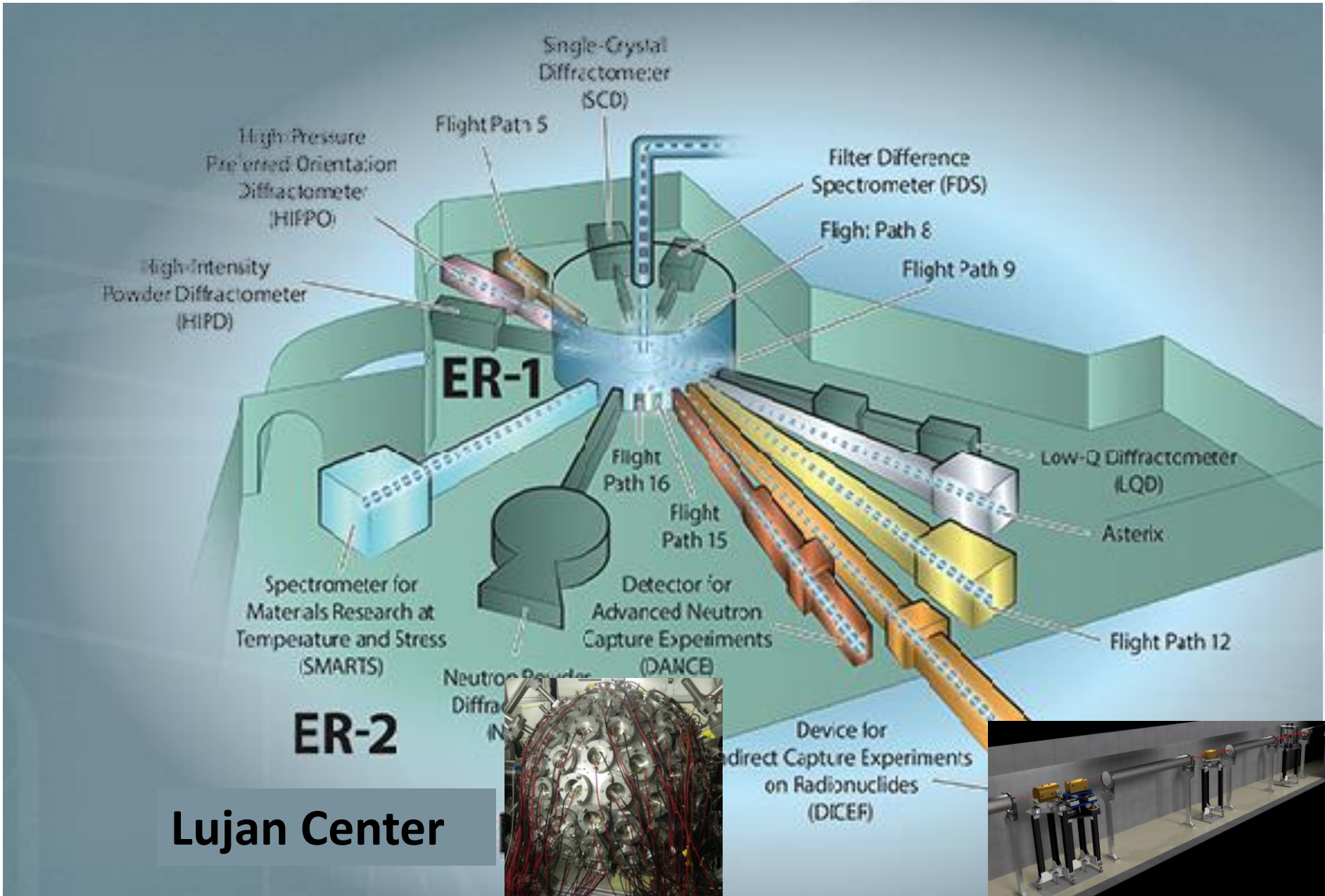
The Los Alamos Neutron Science Center – LANSCE

WNR – High energy neutrons



The Los Alamos Neutron Science Center – LANSCE

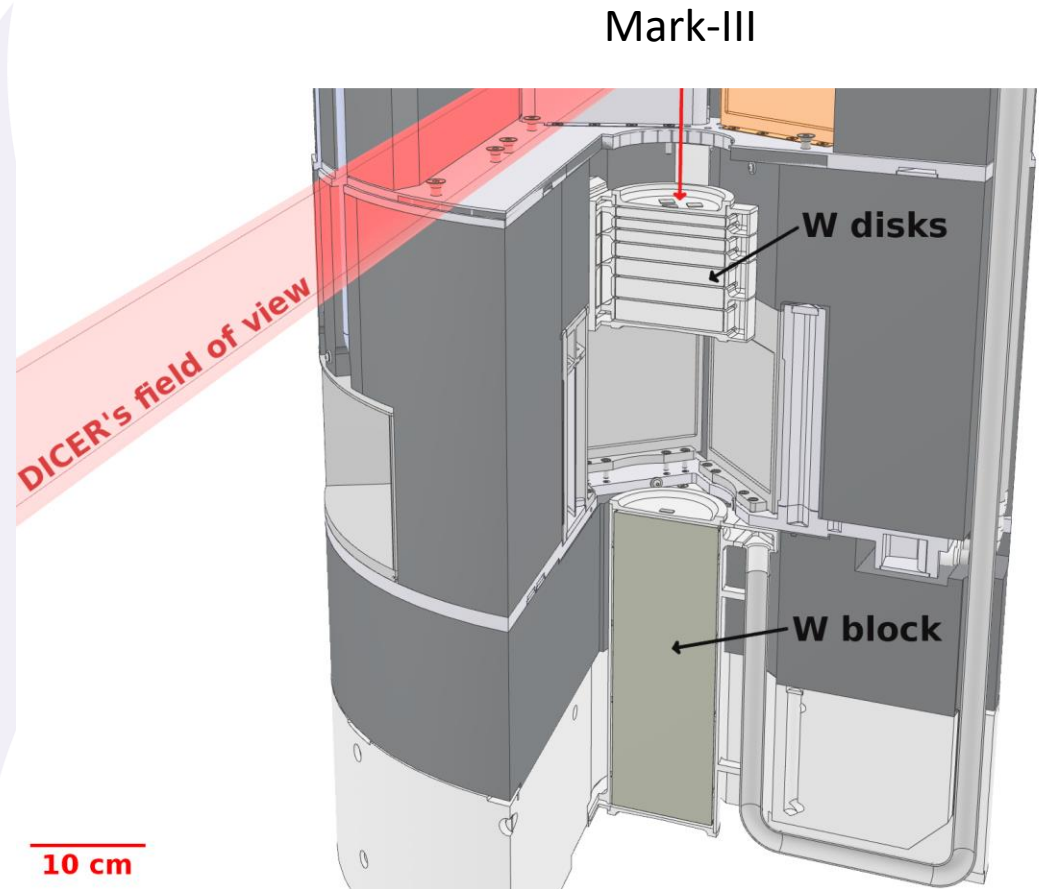
Lujan Center – Low energy neutrons



Lujan Center

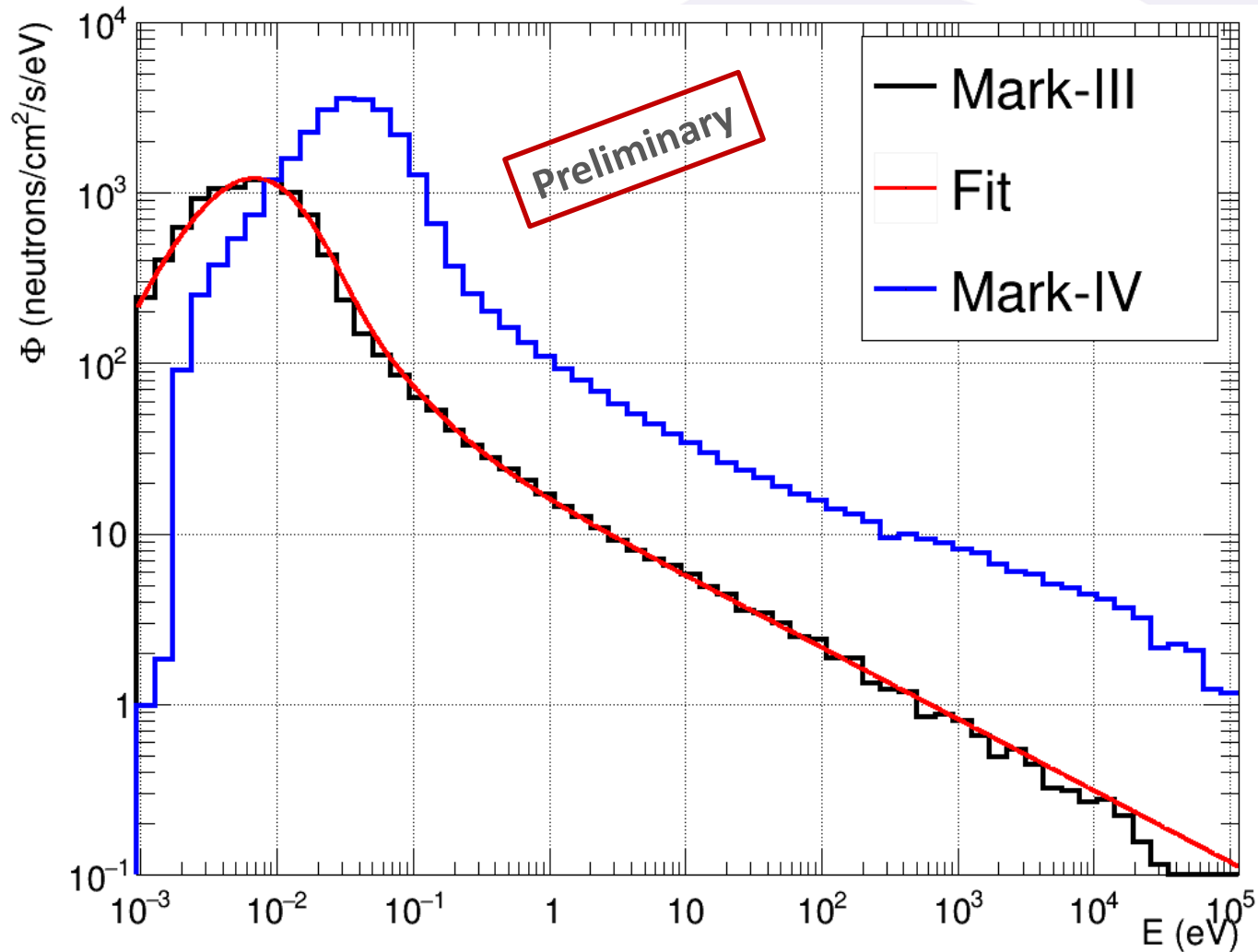
Description of the apparatus: Lujan@LANSCE@LANL

- The Los Alamos Neutron Science Center (LANSCE) is LANL's accelerator complex
- DICER belongs to the Lujan Center instruments which serve material and nuclear science studies.
- Neutrons are spallation products
- 800MeV protons impinge on a split W target at a 20 Hz duty cycle.
- DICER points to the liquid hydrogen moderator
- DICER flux spans from 0.2 meV – 100 keV
- Total: $\sim 6 \times 10^7$ n/s/cm²



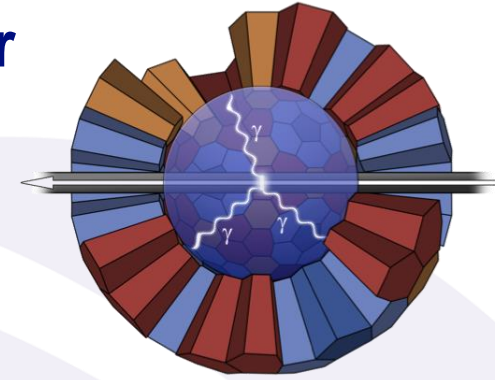
Description of the apparatus: Neutron spectrum

- Mark-IV provides an enhanced keV spectrum compared to Mark-III
- Mark-IV is expected to improve the neutron energy resolution

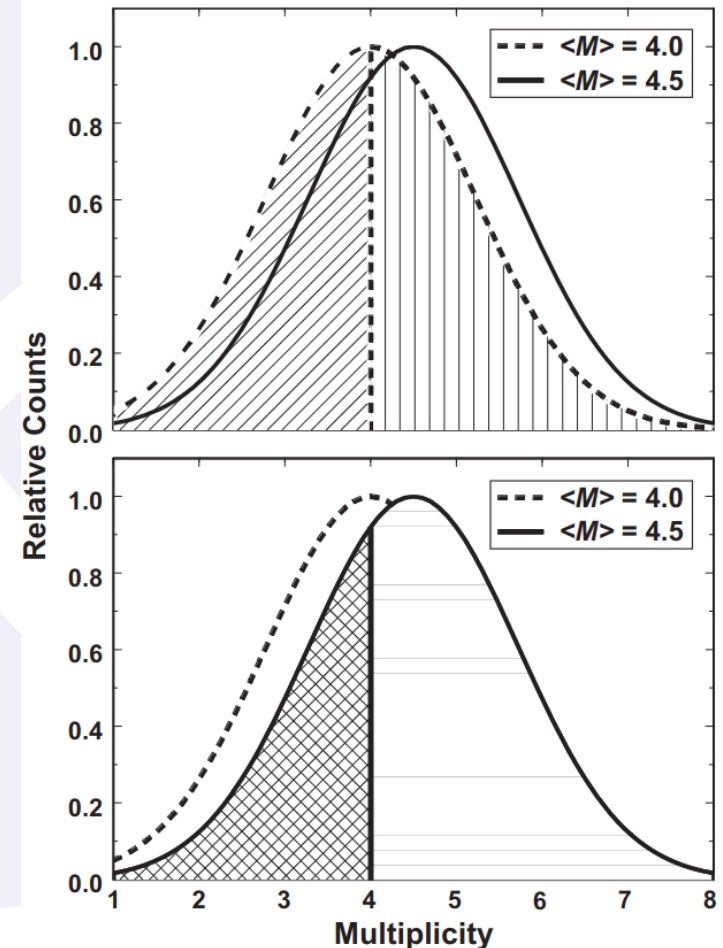
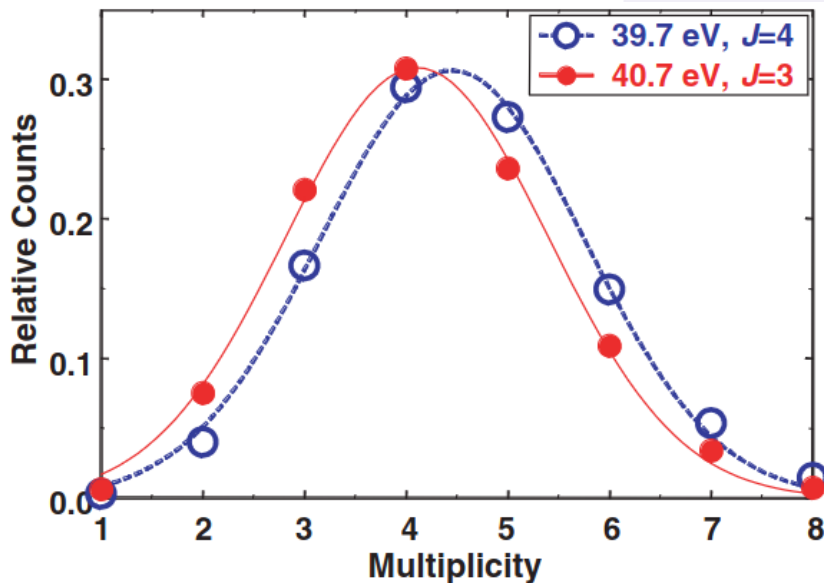


$n+^{149}\text{Sm}$: Capture and transmission – Nuclear Criticality Safety Program

- Neutron poison that doesn't decay away
- Detector for Advanced Neutron Capture Experiments (DANCE)
- $\sim 4\pi$ calorimeter
- DANCE to get the capture yields
- DANCE also provides multiplicities
- Different multiplicity distributions for different spins
- DANCE is used as a spinometer



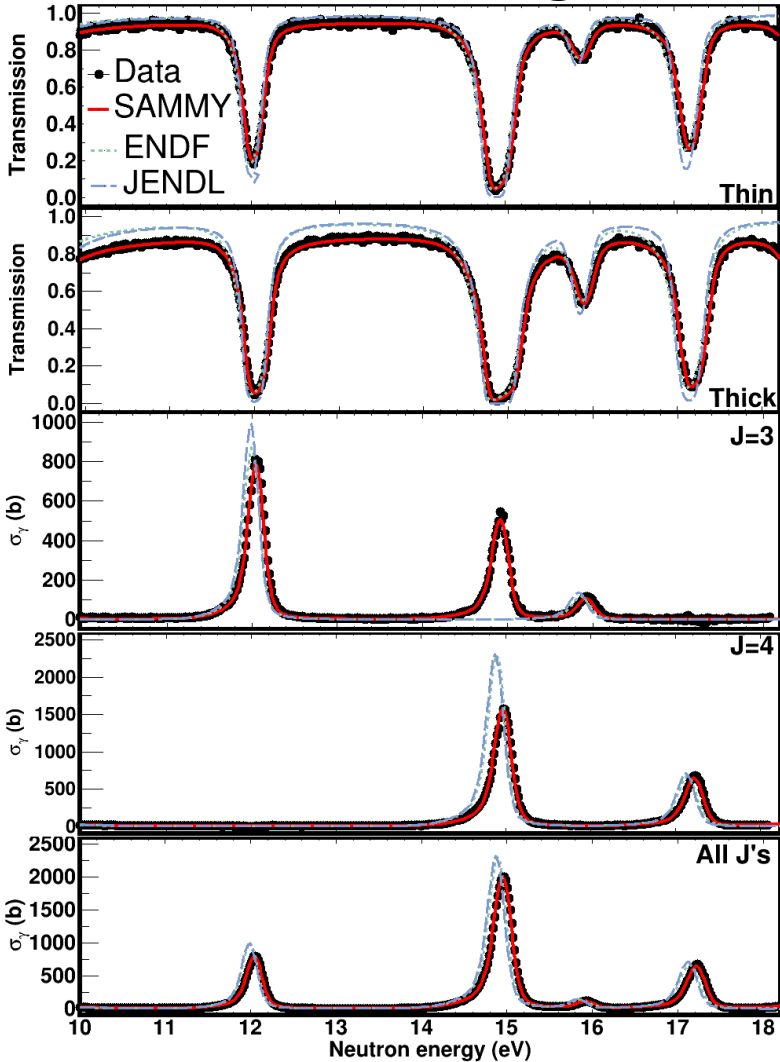
PHYSICAL REVIEW C 76, 025804 (2007)



R-Matrix analysis : Resonance parameters

- Fits in capture and transmission data using SAMMY
- About 40 spins were incorrectly assigned
- Resolved 58 new resonances (215 vs 157 in evaluations)

Resolved doublet @ 15 eV



Evaluated Γ_n is too large

