Neutron Spectroscopic Measurement for Studying Nuclear Level Density via Fusion Evaporation Route

Kaushik Banerjee

VECC

30 MeV Medical Cyclotron

K-130 Cyclotron

K-500 Cyclotron

Experimental technique to determine NLD

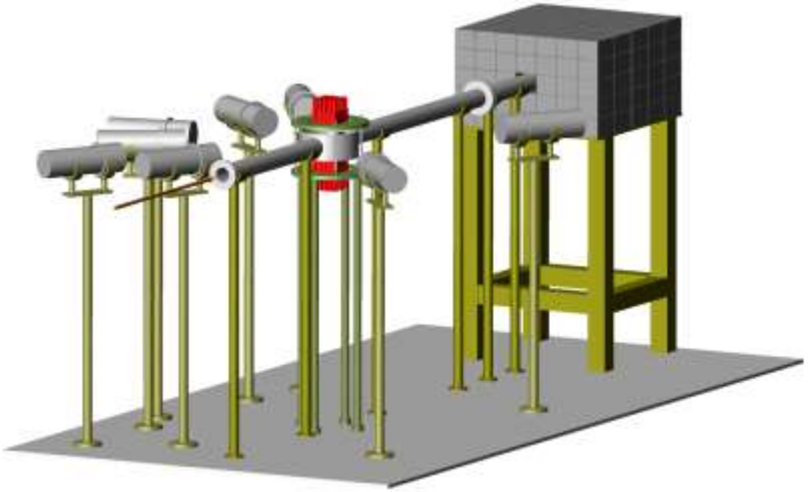
(i) Nuclear Level counting
(ii) Measurement of neutron resonance spacing
(iii) Analysis of primary gamma ray spectrum using the Oslo method
(iv) Shape method
(v) Backward angle particle evaporation spectrum
(vi) High resolution spectrum from (p,p')

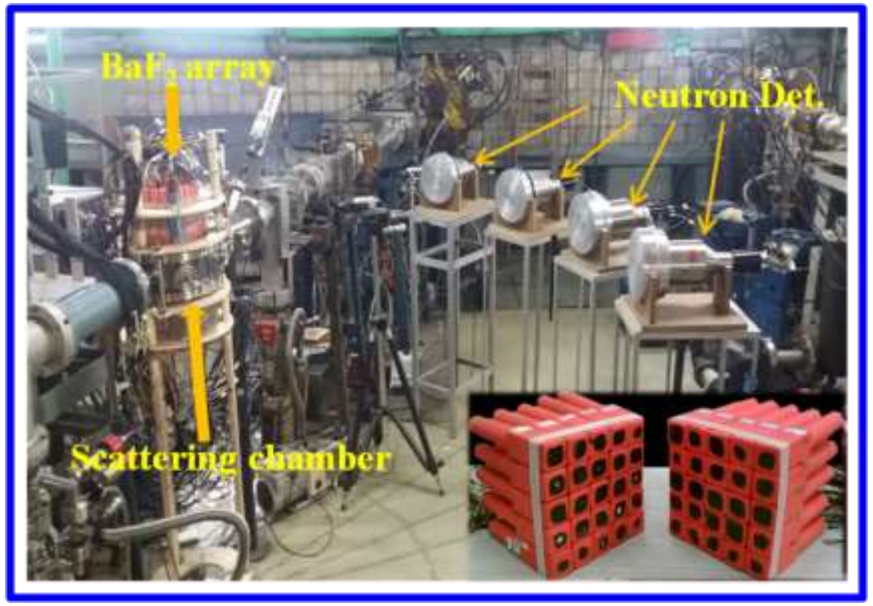
Experimental Nuclear Level Density can be determined from the measured evaporated particle spectrum

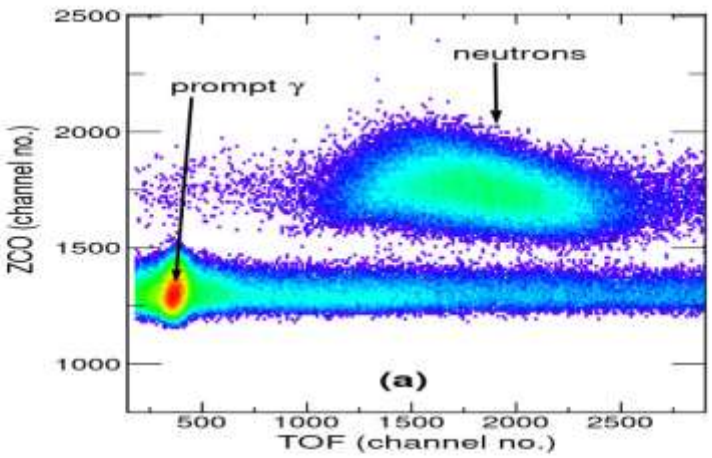
Phys. Rev. C 51, 614 (1995)

$$\rho_{\exp}(E) = \rho_{\text{model}}(E)\frac{(d\sigma/d\varepsilon)_{\exp}}{(d\sigma/d\varepsilon)_{\text{model}}}$$

$$E = E_{CN}^{*} - S_n - \varepsilon - E_R$$







Detectors:- Liquid Scintillators(BC501A) for neutrons and BaF_2-array for gamma-ray

Nuclear level density models:

Back Shifted Fermi-gas model : Considering the pairing effect, the tendency that fermions have couple by pair, even odd staggering. Δ and a are the free parameter.

$$\rho(E^*) = \frac{1}{12\sqrt{2}\sigma} \frac{\exp[2\sqrt{a(E^* - \Delta)}]}{a^{1/4}(E^* - \Delta)^{5/4}}$$

Shell Effect in Nuclear Level Density

$$a = \tilde{a}\left[1 + \frac{\Delta S}{U}\{1 - exp(-\gamma U)\}\right]$$

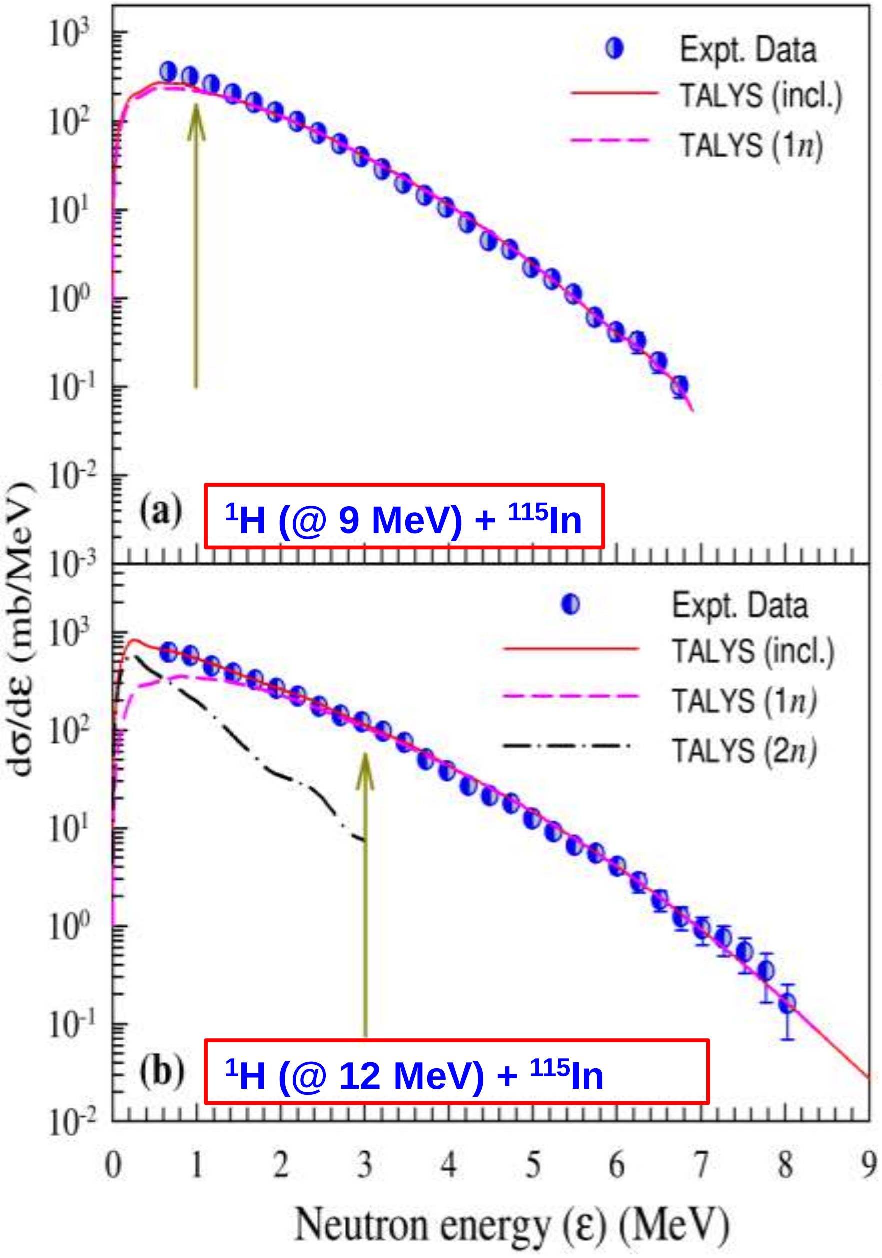
$$a = \frac{A}{k} \qquad \gamma^{-1} = \frac{0.4A^{4/3}}{\tilde{a}}$$

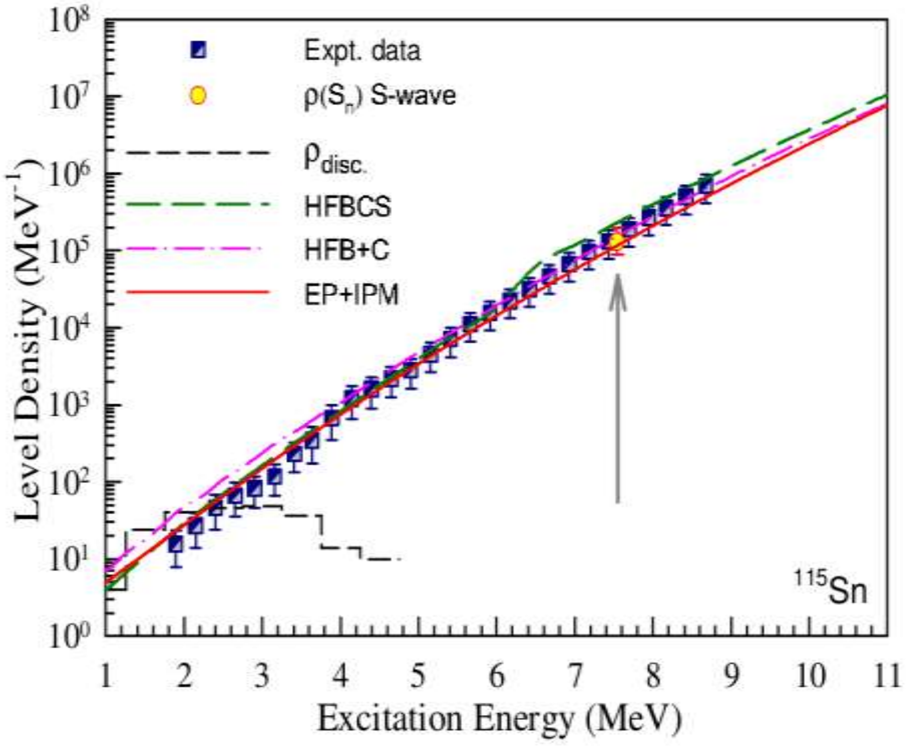
Nuclear Data Sheets 110 (2009) 3107

ΔS is shell correction, the difference between experimental mass of the nucleus and its liquid drop mass, γ shell damping factor

A. V. Ignatyuk et.al Sov. J. Nucl. Phys. 21, 255 (1975)

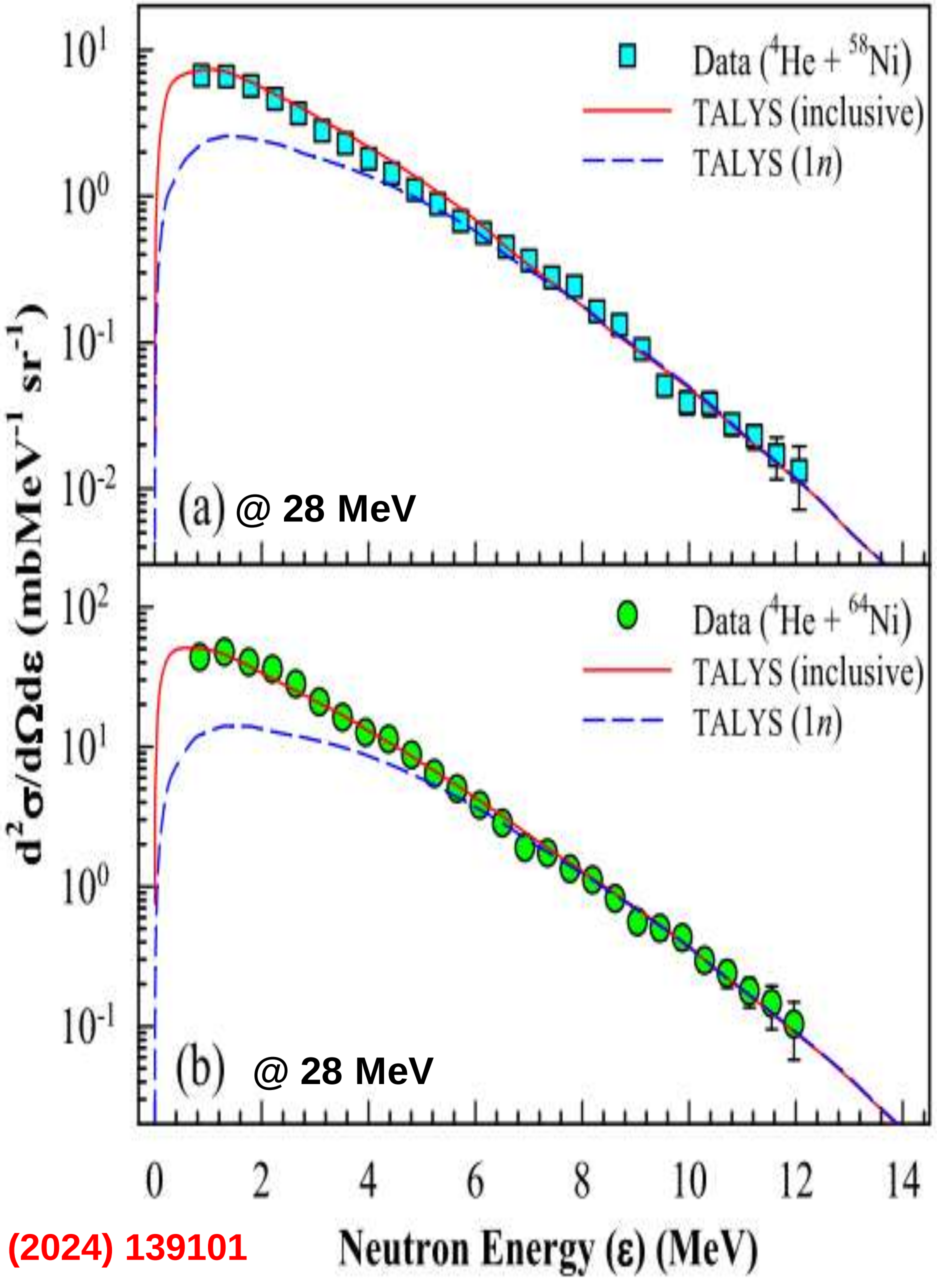
Nuclear Level Density using Neutron Evaporation Method

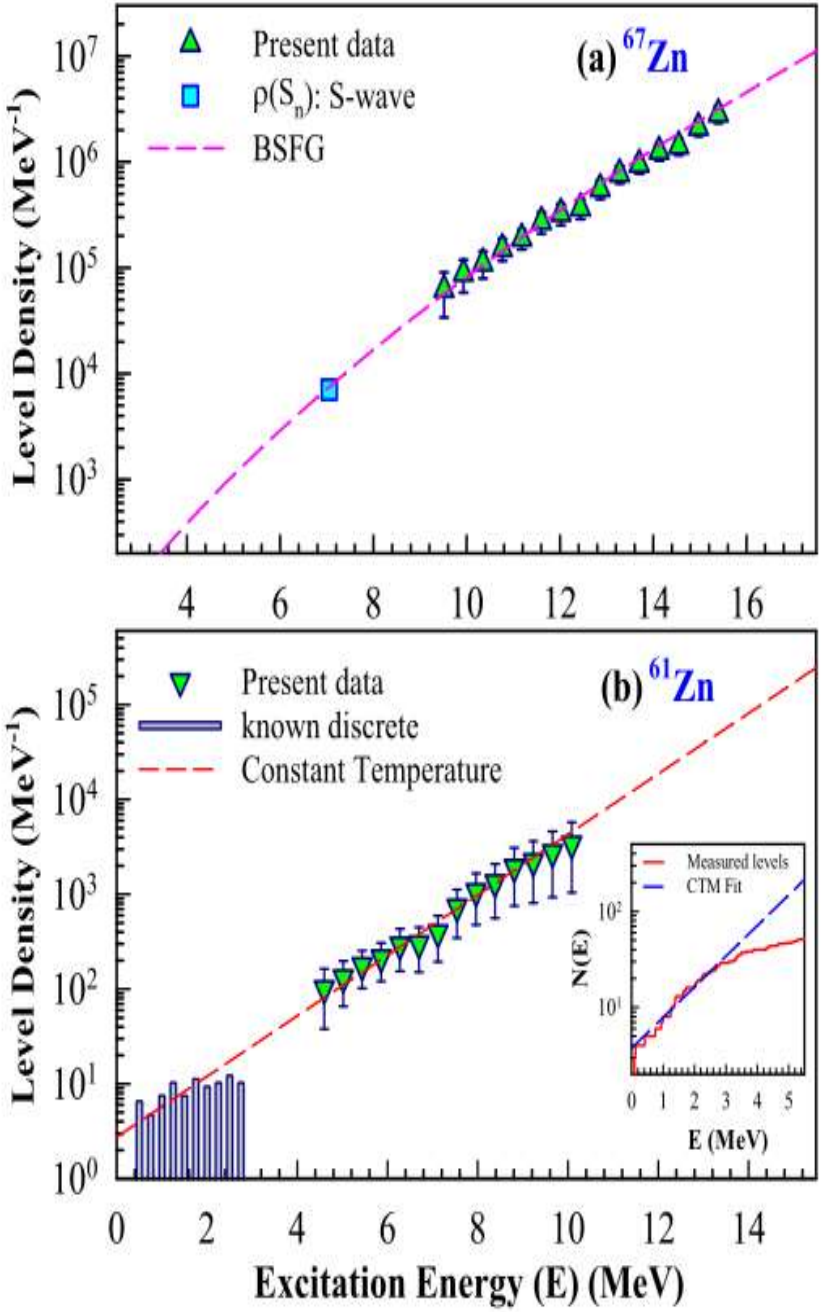




P. Roy *et al.*, Eur. Phys. J. A 57 (2021) 48

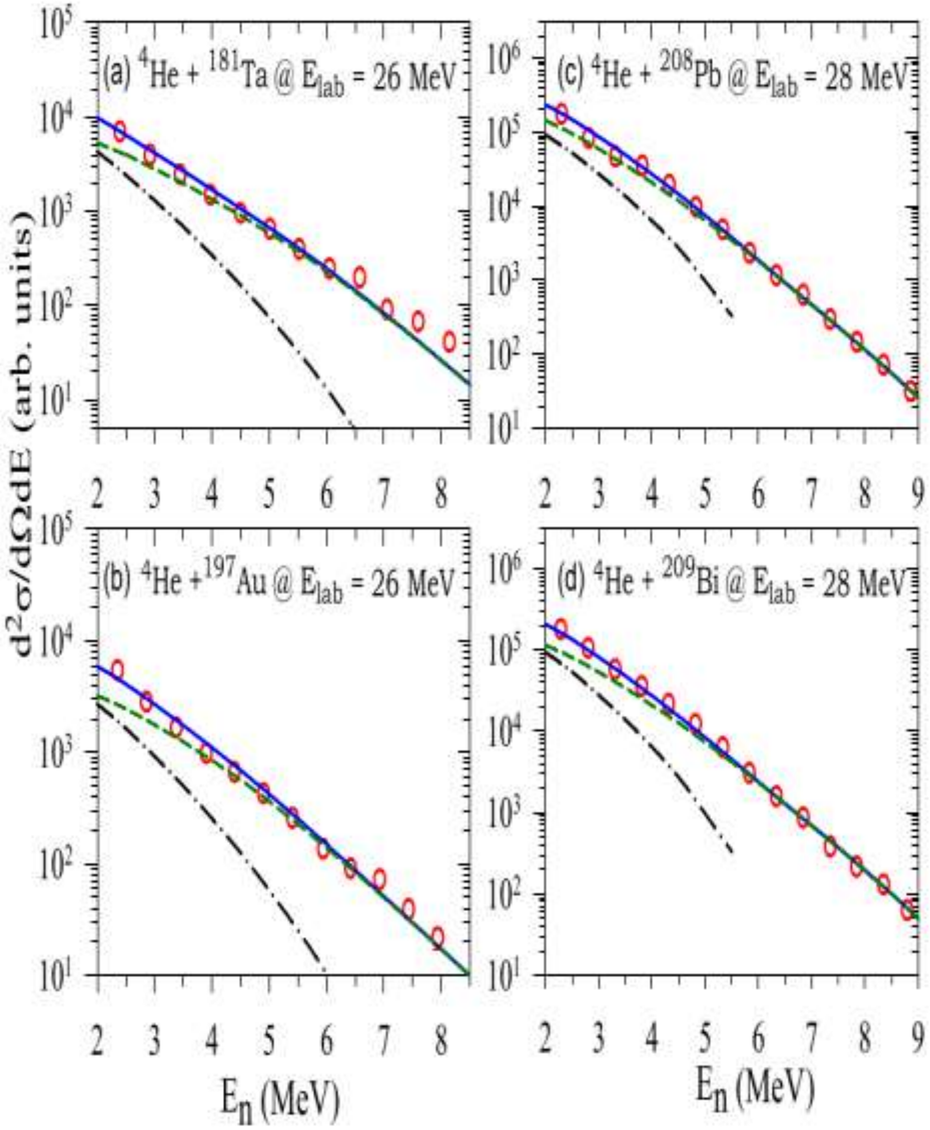
Nuclear Level Density using Particle Evaporation Method

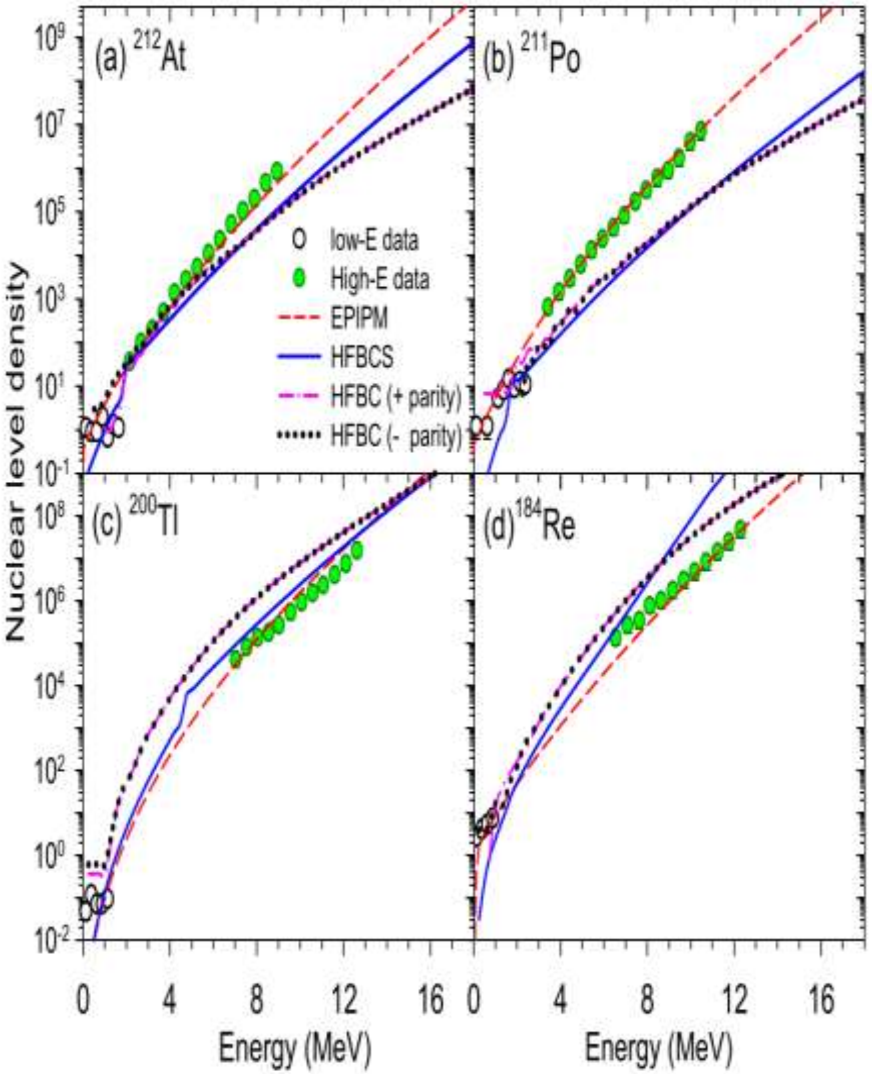




P. Roy *et al.*, Phys. Lett. B 859 (2024) 139101

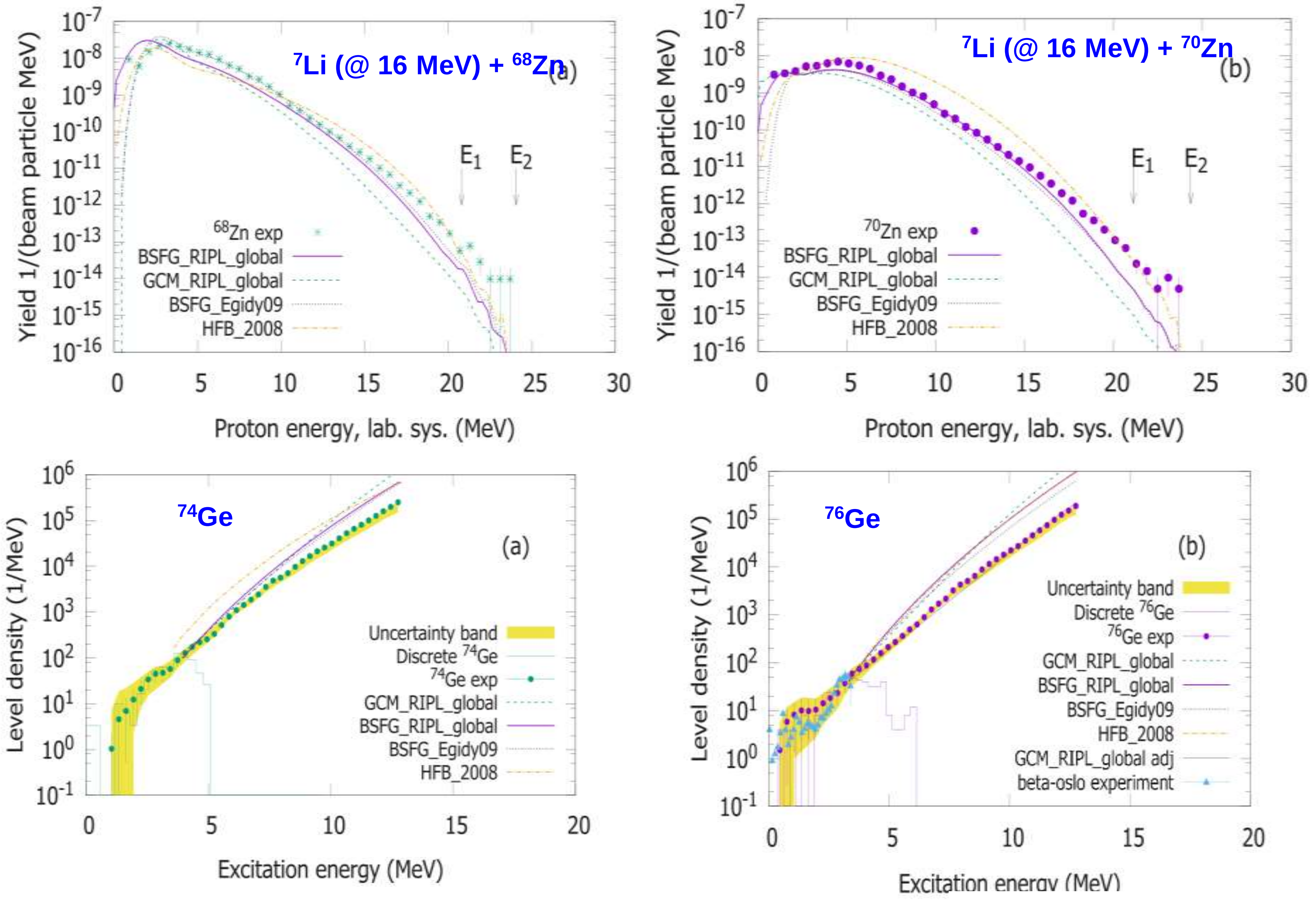
Nuclear Level Density using Neutron Evaporation Method





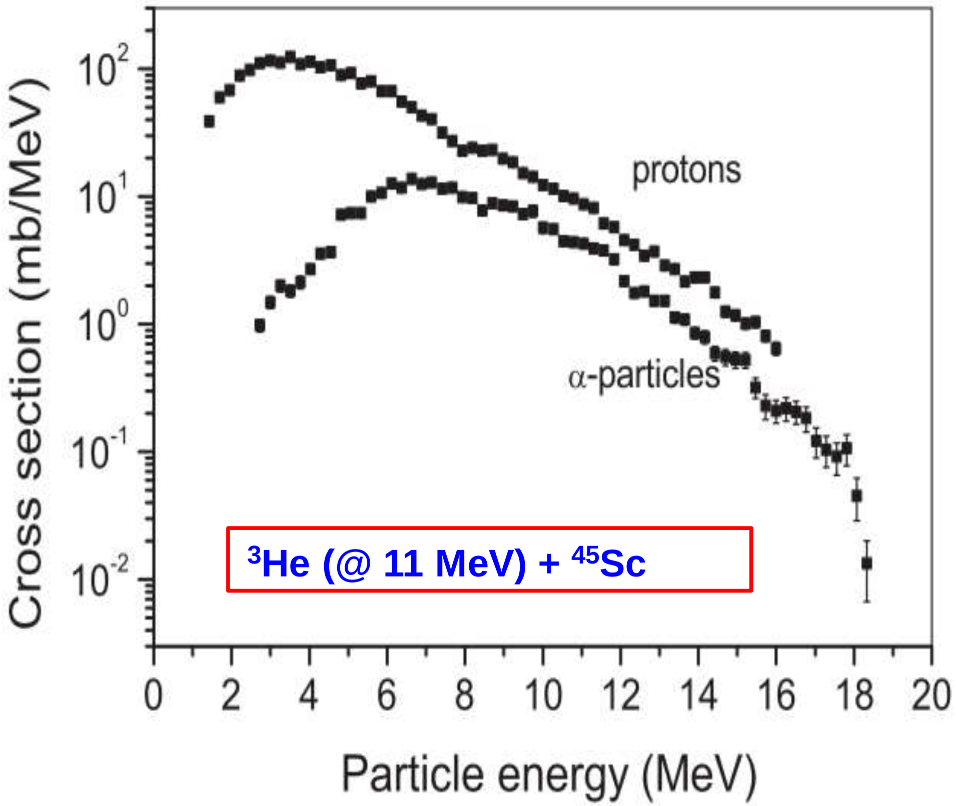
B. Dey *et al.*, Phys. Lett. B 789 (2019) 634

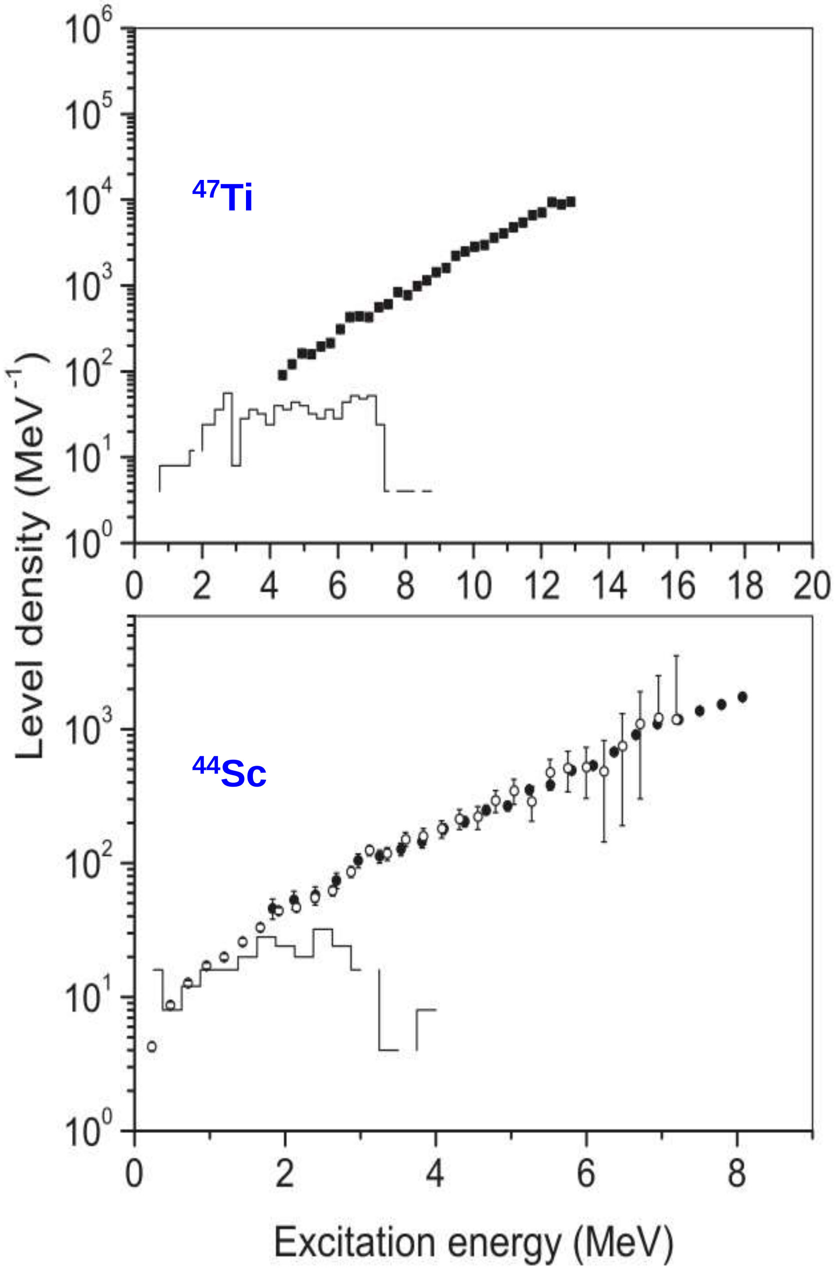
Nuclear Level Density using Proton Evaporation Method



A. V. Voinov *et al.*, Phys. Rev. C 99 (2019) 054609

Nuclear Level Density using Proton and Alpha Evaporation Method

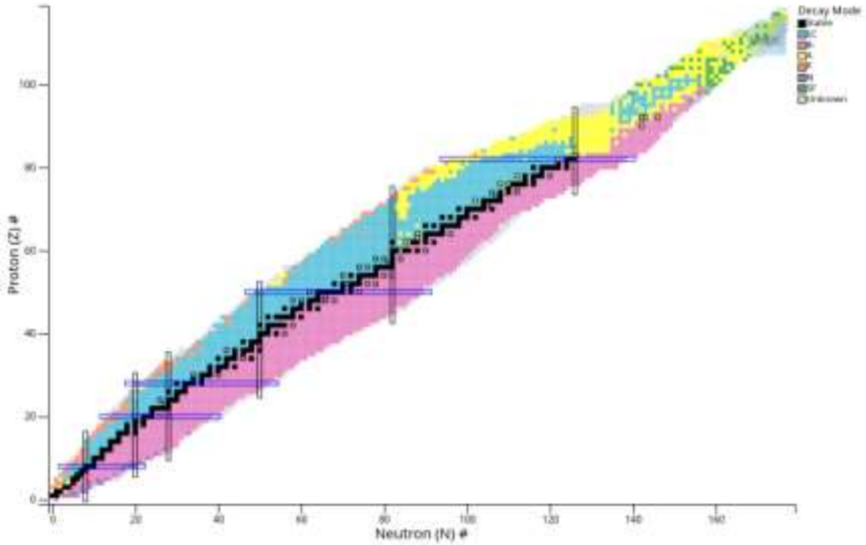


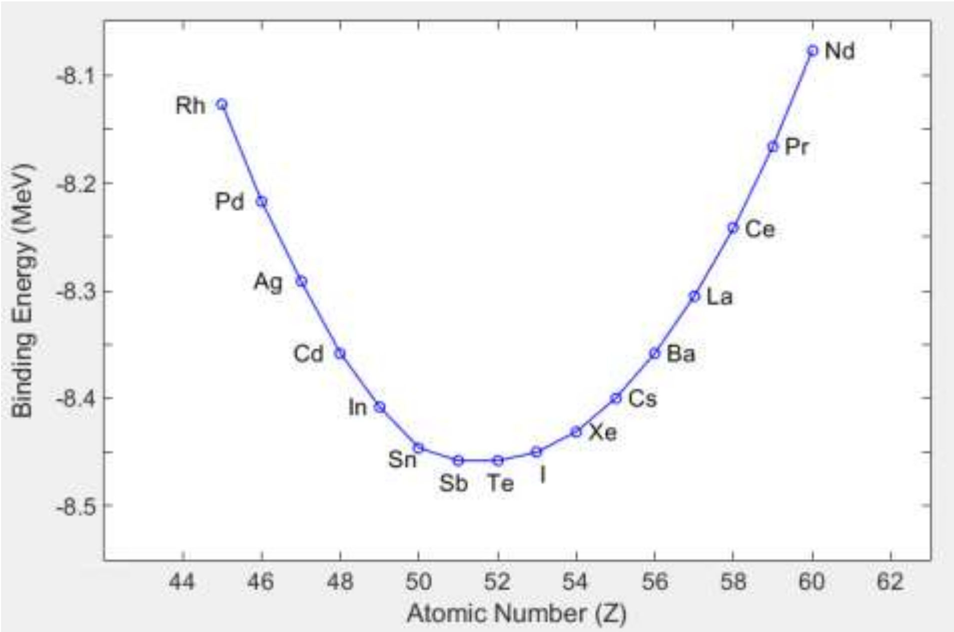


A. V. Voinov *et al.*, Phys. Rev. C 77 (2008) 034613

Isospin dependence of Nuclear Level Density

Isospin dependent expression –





$$a = \alpha A$$

$$a = \frac{\alpha A}{\exp[\beta (N - Z)^2]}$$

$$a = \frac{\alpha A}{\exp[\gamma (Z - Z_0)^2]}$$

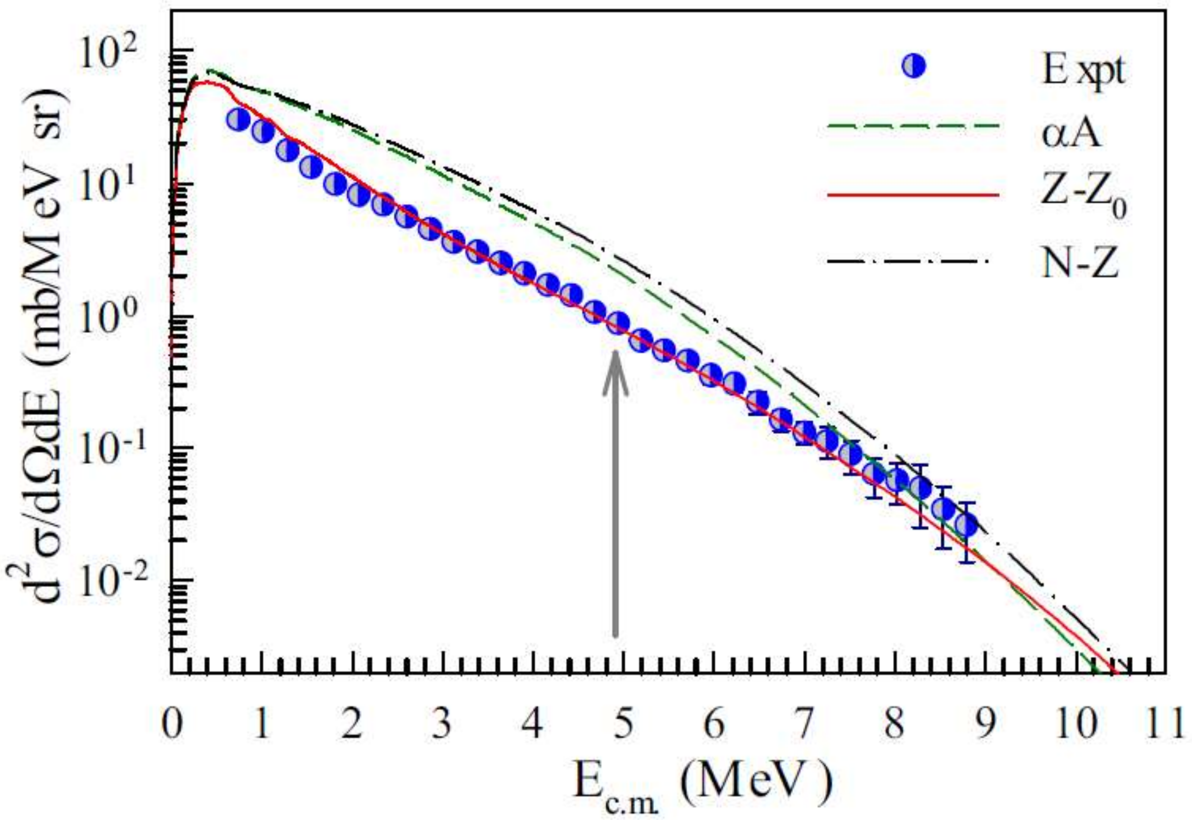
Level densities of nuclei off the stability line were lower than those for nearby nuclei on the stability line

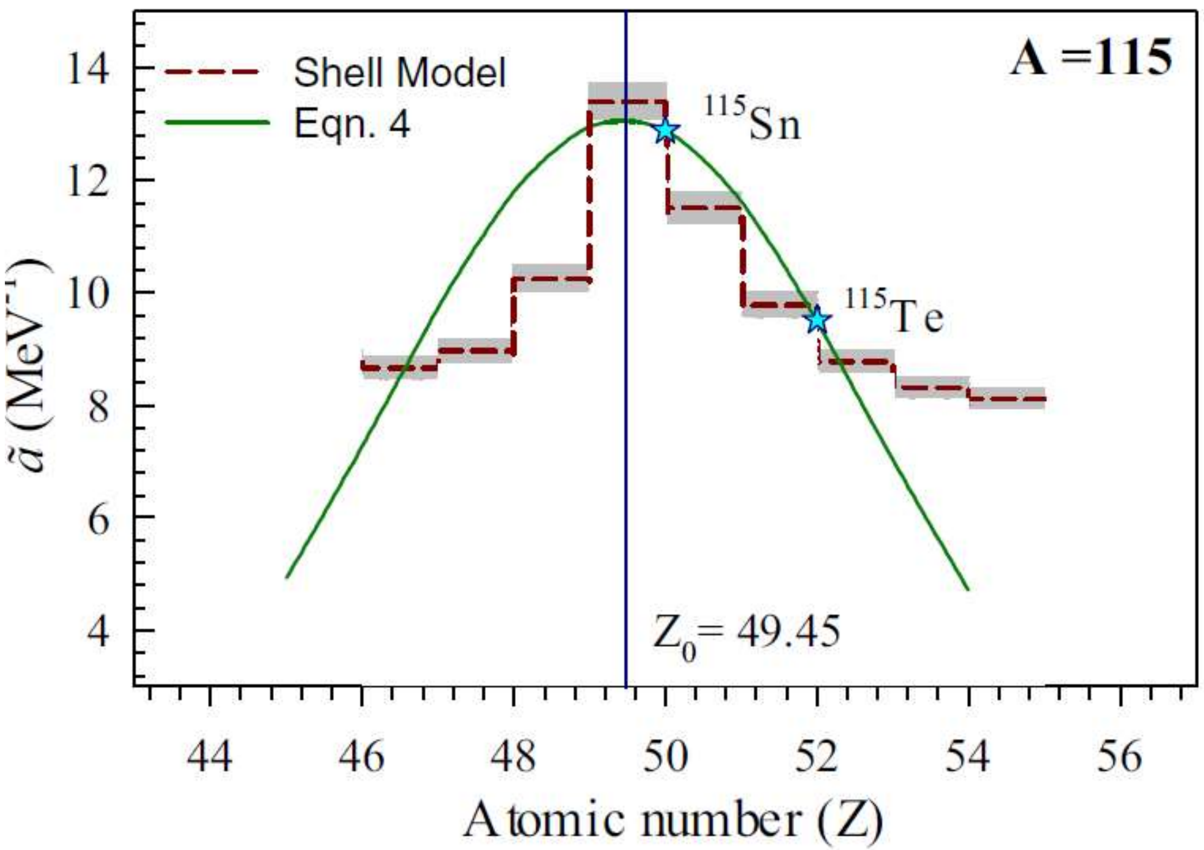
$$Z_0 = \frac{0.5042A}{(1 + 0.0073A^{2/3})}$$

$20 \leq$ A ≤ 70 S.I. Al-Quraishi *et al.*, PRC 63, 065803 (2001)

$20 \leq$ A ≤ 110 S.I. Al-Quraishi *et al.*, PRC 67, 015803 (2003)

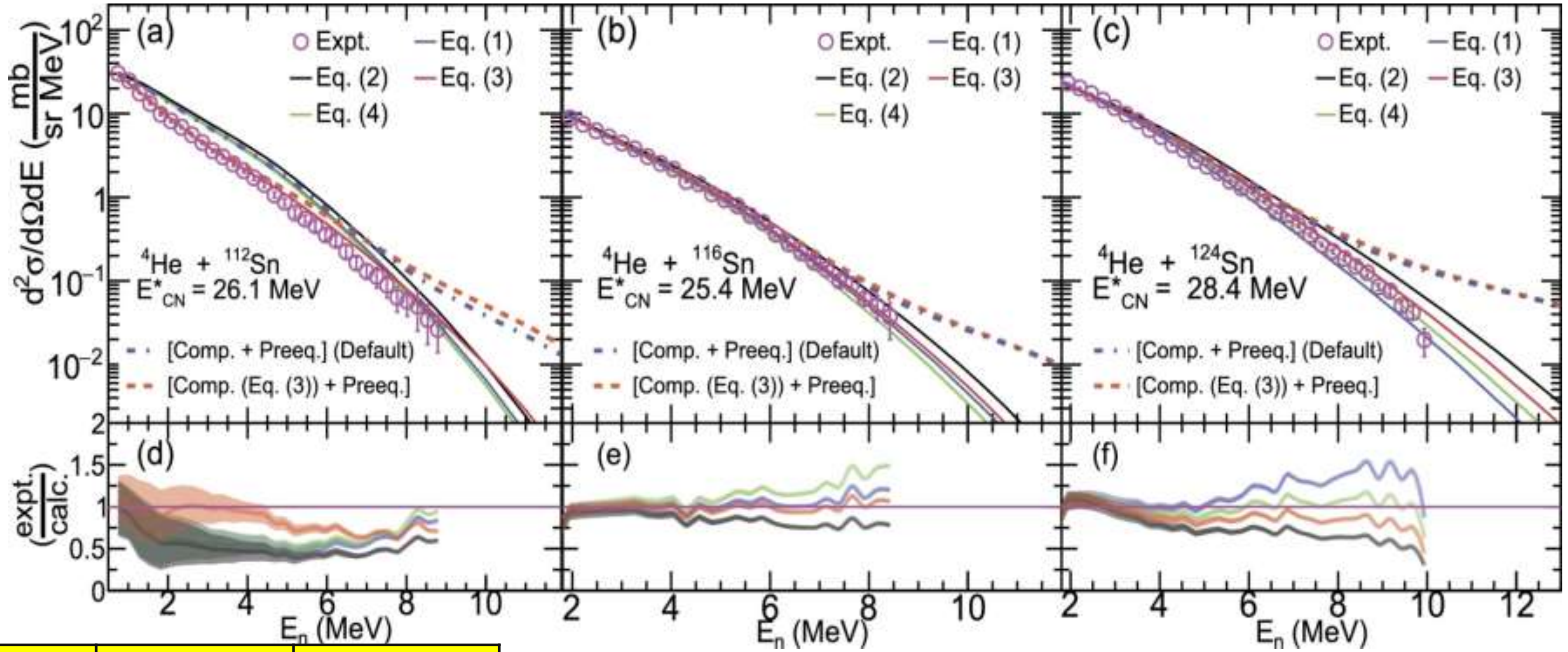
Isospin dependence in NLD in A =115 nuclei populated using $^{4}He + {}^{112}Sn$ and $p + {}^{115}In$ reactions





P. Roy et. al., Phys Rev C 102 (2020) 061601R

NLD in 120 mass region, Reactions studied: ^{4}He + $^{112,116,124}Sn$ $\rightarrow$ $^{115,119,127}Te$ + n E_{lab}= 26 MeV



Populated Nucleus	Deformation (β_2)	$\lvert(Z-Z_0)\rvert$	$\lvert(N-Z)\rvert$
^{115}Te	0.25	2.5	11
^{119}Te	0.24	1.0	15
^{127}Te	0.08	2.1	23

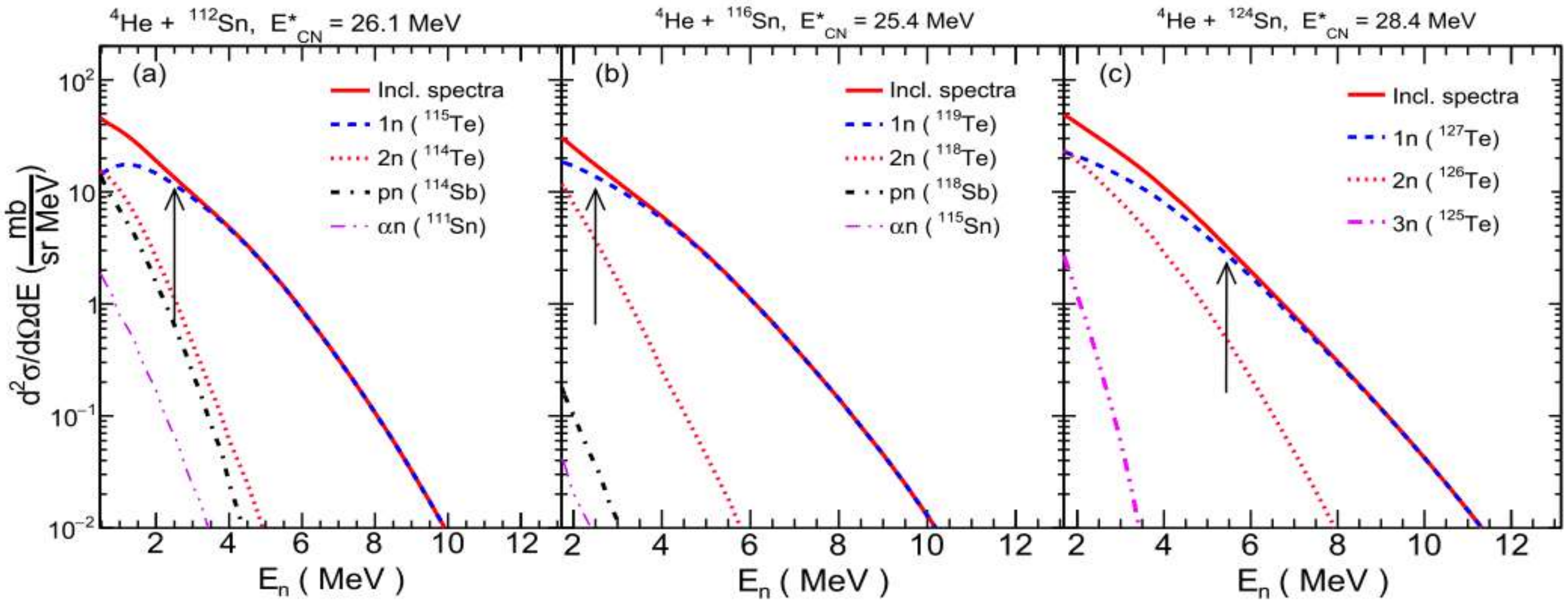
$$\tilde{a} = \alpha A \quad \text{---- (1)}$$

$$\tilde{a} = \frac{\alpha A}{exp[\beta(N-Z)^2]} \quad \text{---- (2)}$$

$$\tilde{a} = \frac{\alpha A}{exp[\gamma(Z-Z_o)^2]} \quad \text{---- (3)}$$

$$\tilde{a} = 0.04543\, r_0^3 A + 0.1355\, r_0^2 A^{2/3} B_s + 0.1426\, r_0 A^{1/3} B_k \quad \text{---- (4)}$$

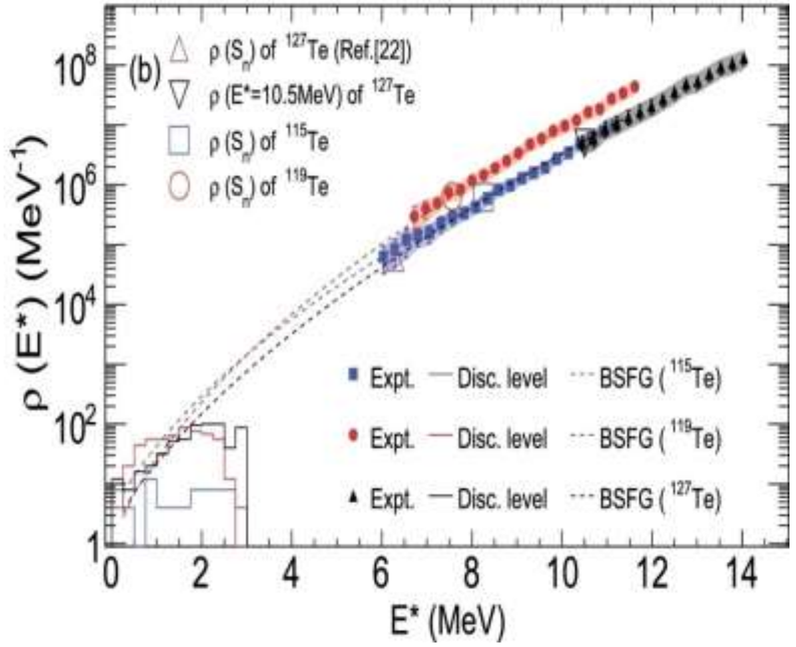
R. Shil, K. Banerjee *et al.*, Phys. Lett. B 831, 137145 (2022)



$$\rho_{exp}(E^*) = \rho_{model}(E^*)\frac{(d\sigma/dE_n)_{exp}}{(d\sigma/dE_n)_{model}}$$

Where, $E^* = E^*_{CN} - S^P_n - E_R - E_n$

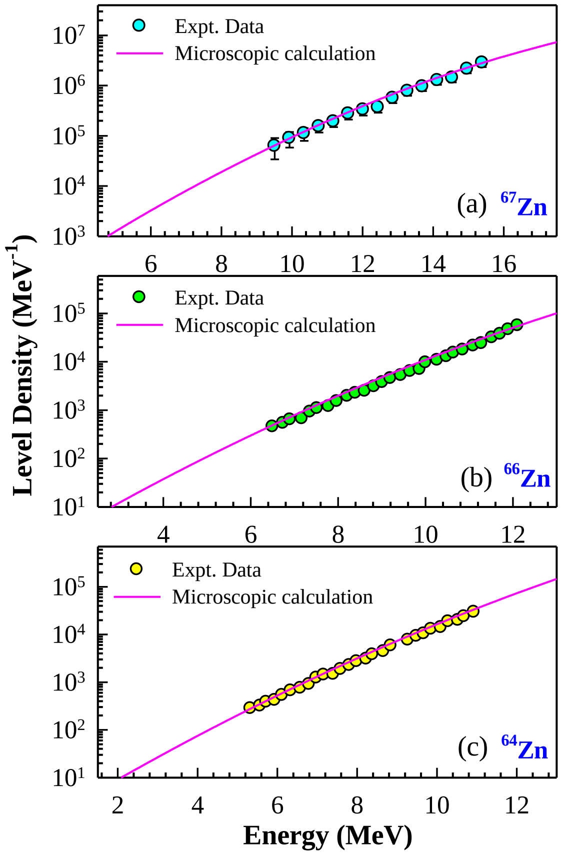
$S^p_n \rightarrow$ **Neutron separation energy of CN.**
$E_R \rightarrow$ **Rotational kinetic energy.**
$E_n \rightarrow$ **Neutron kinetic energy.**



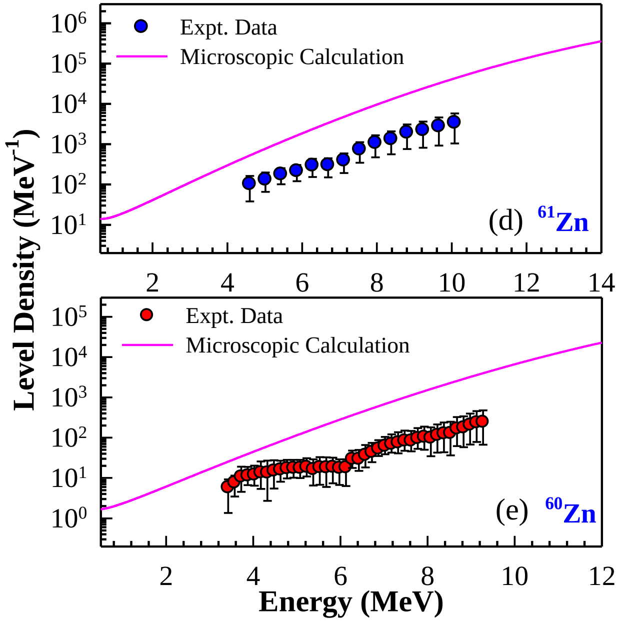
R. Shil, K. Banerjee *et al.*, Phys. Lett. B 831 (2022) 137145

Isospin dependence of NLD in Zn isotopes

Stable Zn isotopes: Excellent agreement with calculation



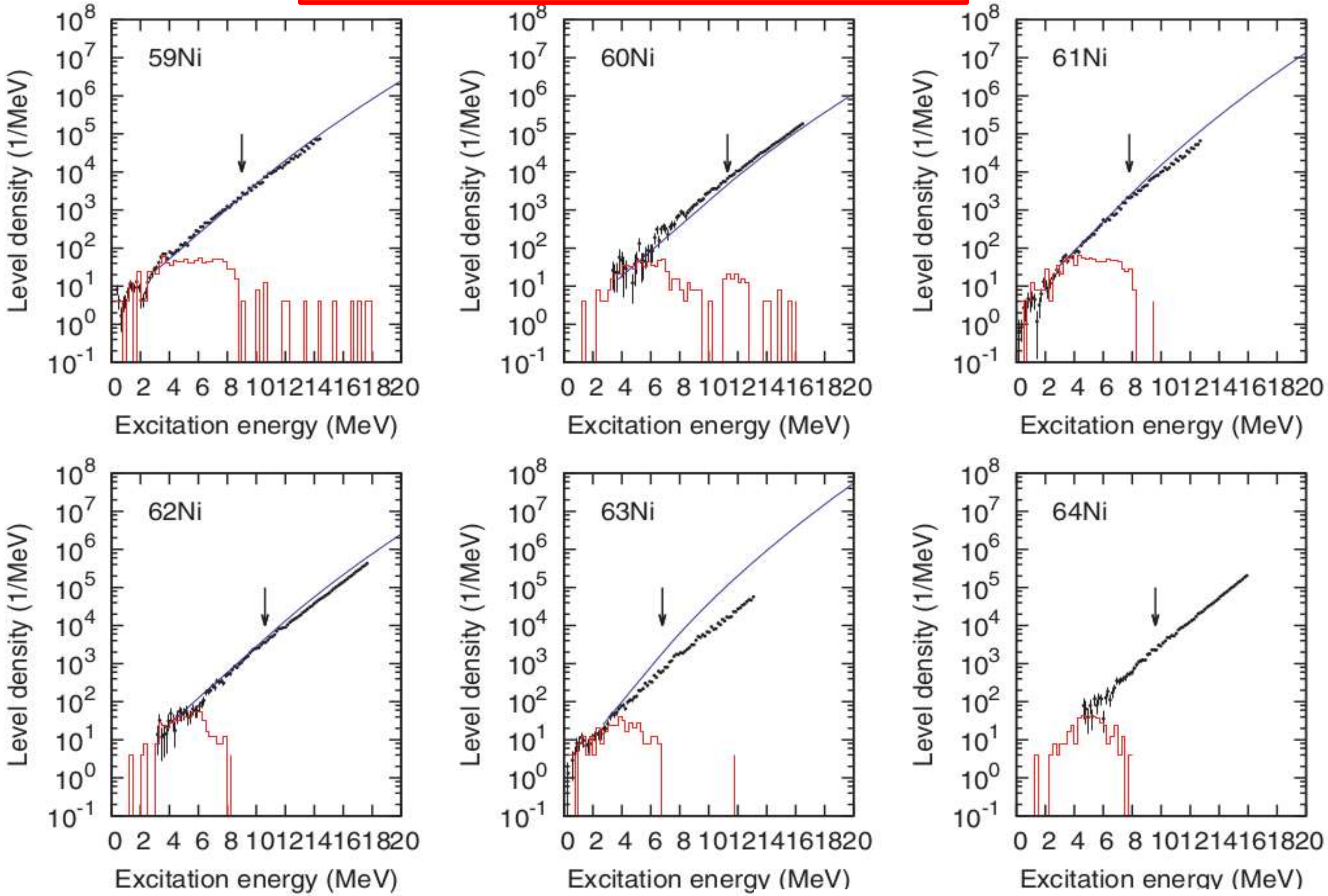
NLD of unstable isotopes: An order of magnitude lower than prediction!



Microscopic calculation using EP + IPM model
N. Quang Hung Phys. Rev. Lett. 118 (2017) 022502

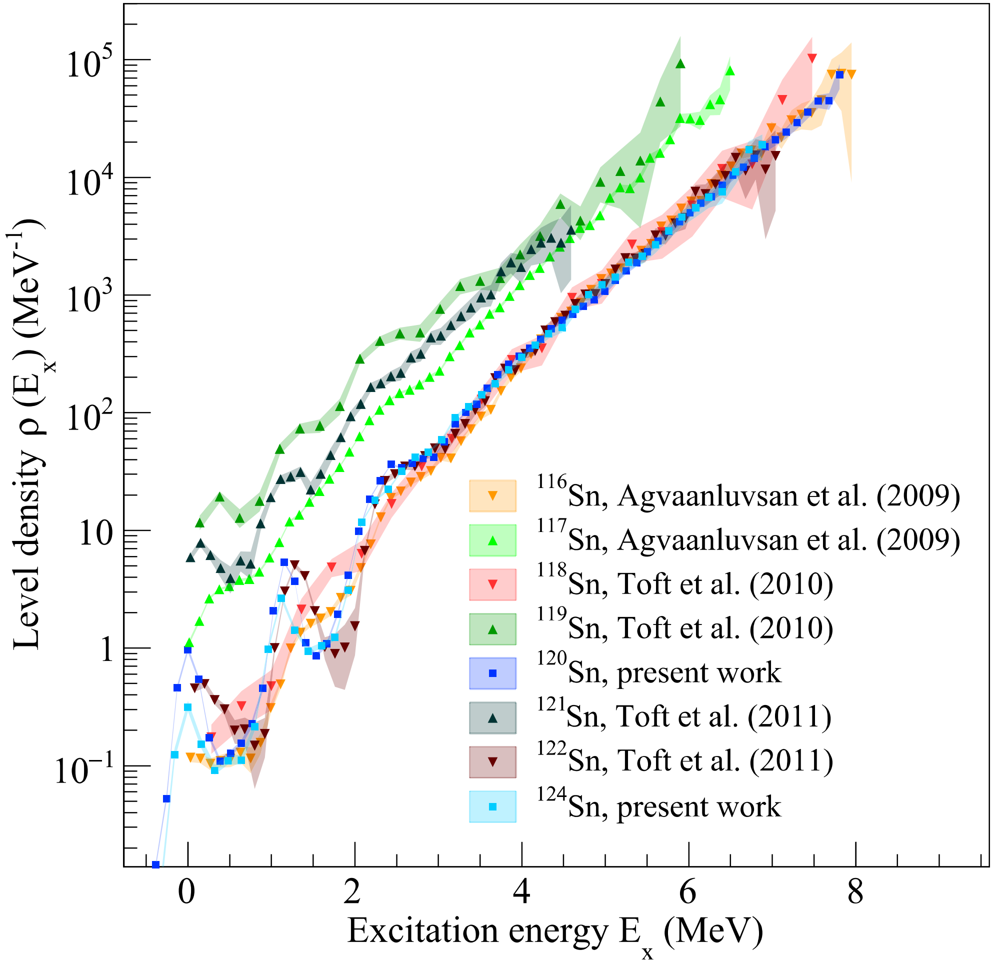
P. Roy *et al.*, Phys. Lett. B 859 (2024) 139101
A. P. D. Ramirez et. al., Phys. Rev. C 88, 064324 (2013)
D. Soltesz et. al., Phys Rev C 103, 015802 (2021)

Nuclear Level Density using Proton Evaporation Method



A. V. Voinov *et al.*, EPJ Web of Conf. 21 (2012) 05001

Nuclear Level densities in Sn-isotopes



M. Markova et. al., Phys. Rev. C 106, 034322 (2022)

Collective enhancement in Nuclear Level Density

Collective excitation (many-body effect) and its contribution to nuclear level density:

Additional contribution to NLD beyond the independent particle model may come from the collective properties (rotation and/or vibration)

Collective Rotational bands are build on each intrinsic or single-particle state (for a deformed system)

Ignatyuk proposed $\rho(E^*, J)$ *can be described as*

$$\rho(E^*, J) = \rho_{int}(E^*, J) K_{coll}(E^*)$$

$$K_{coll}(E^*) = K_{rot}(E^*) K_{vib}(E^*)$$

A. V. Ignatyuk et.al Sov. J. Nucl. Phys. 29, 450 (1979)

Open Problem:

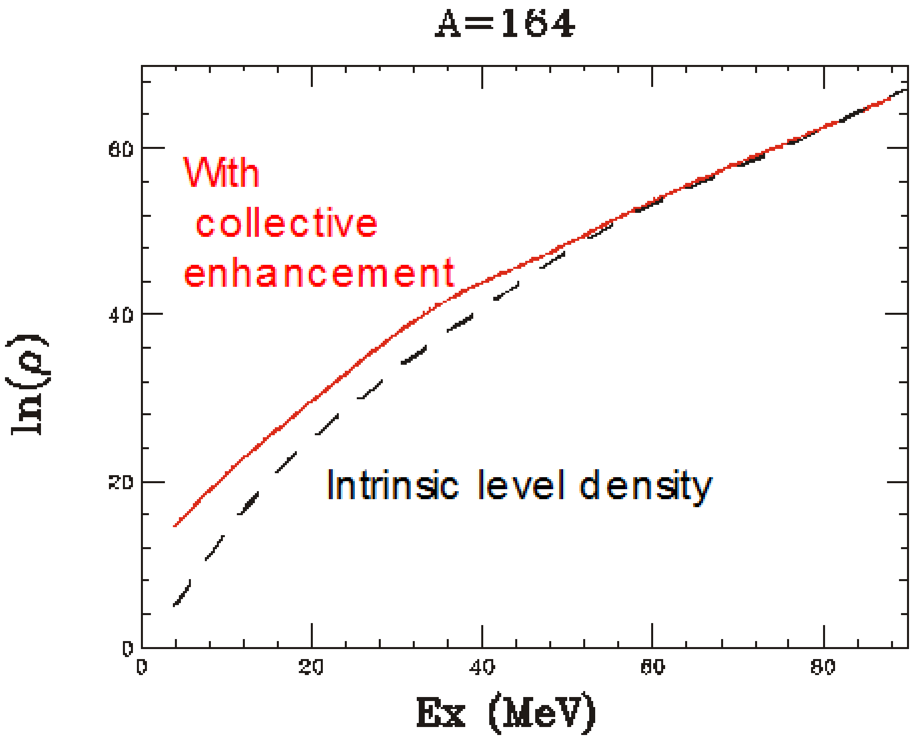
- At what excitation energy does the fadeout of collectivity occur?
- What is the magnitude of the collective enhancement?
- Can these phenomena be determined experimentally?

Enhancement must fade out at higher excitation energies

Bjornholm, Bohr, Mottleson proposed a a critical temperature T_c, beyond which collective contributions in NLD are expected to die out due to gradual damping of long range correlations

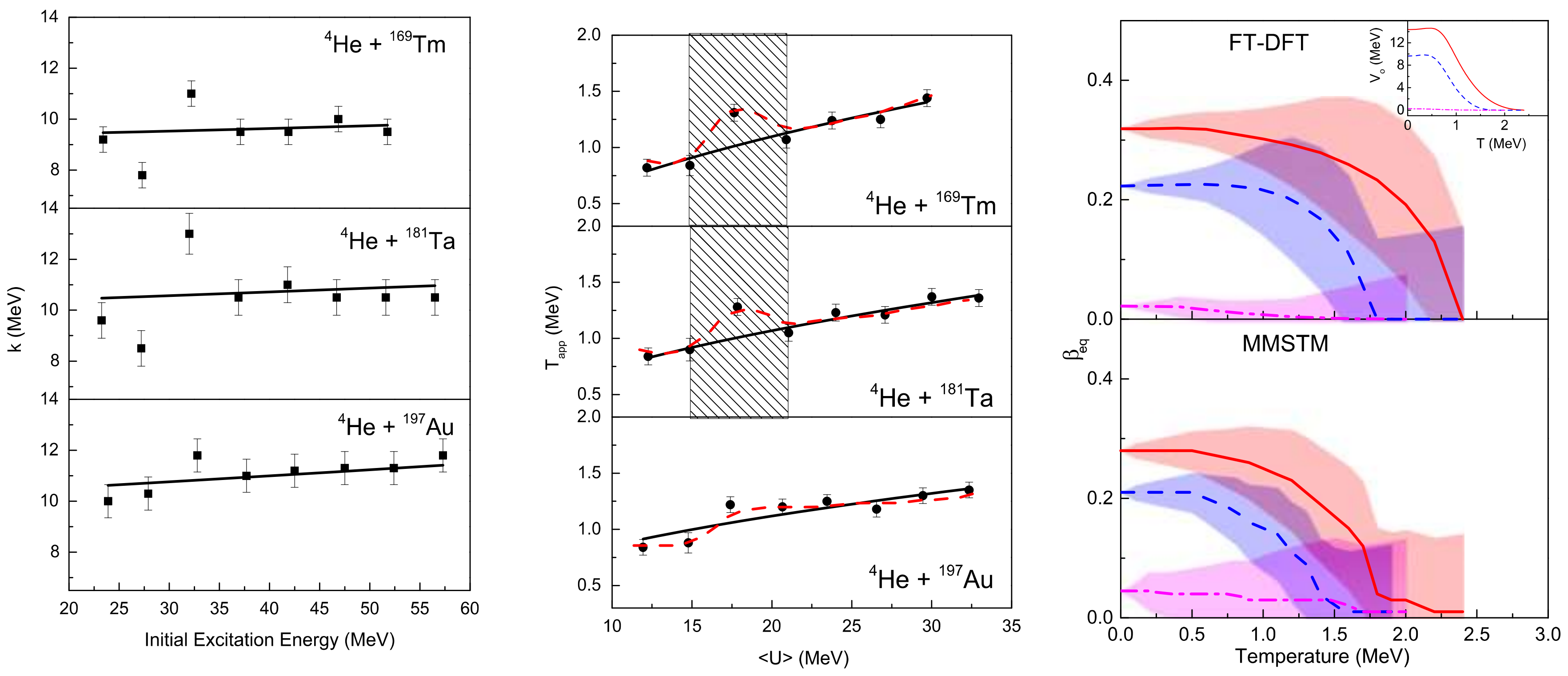
$$T_c = \frac{40\beta_2}{A^{1/3}}\ \text{MeV}$$

β_2 is the ground-state quadrupole deformation parameter



Hansen and Jensen Nuclear Physics A 406 (1983) 236

Fadeout of collective enhancement



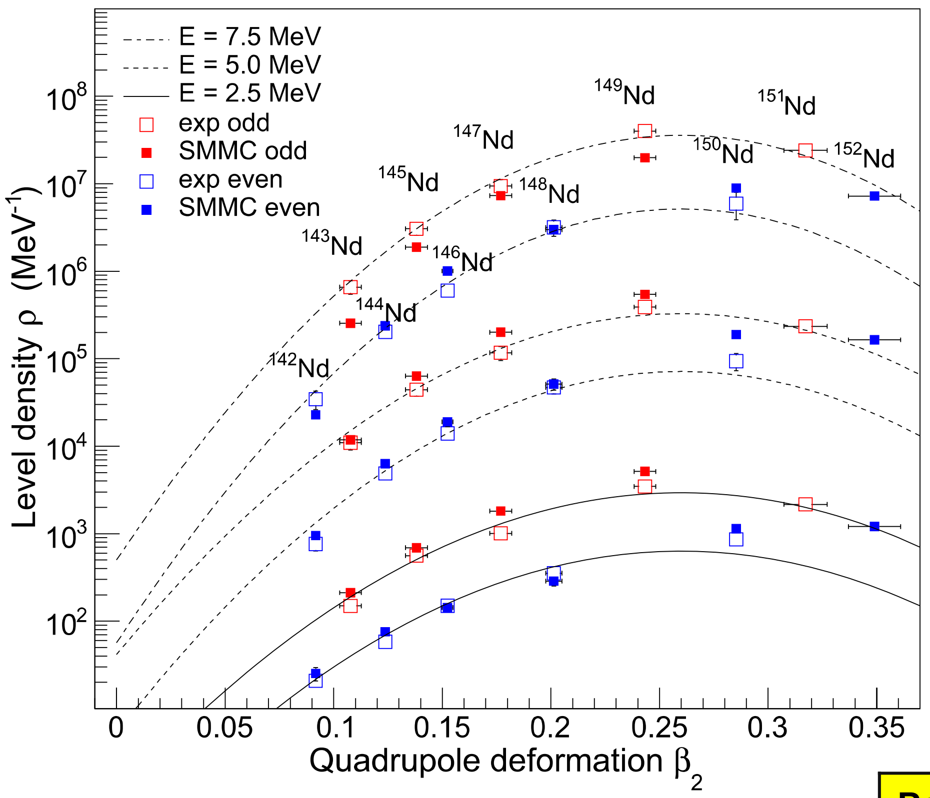
^{4}He + ^{169}Tm->^{173}Lu(β_2 = 0.286) + n

^{4}He + ^{181}Ta -> ^{185}Re (β_2 = 0.221) + n

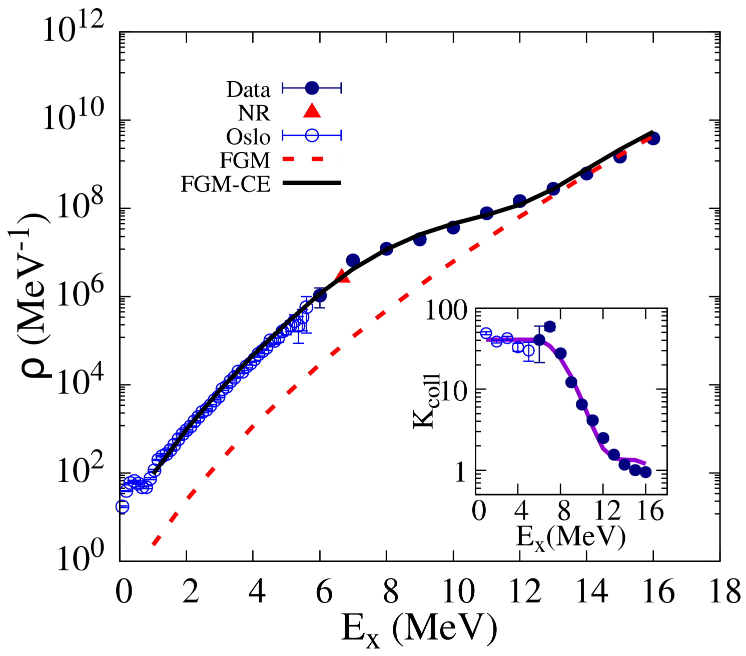
^{4}He + ^{197}Au-> ^{201}Tl (β_2 = 0.044) + n

K. Banerjee et. al. Phys Lett B 772, (2017) 105

Collective enhancement



^{7}Li + ^{169}Tm->^{171}Yb (E* = 25.5 -27.5 MeV) [triton transfer]



Collective enhancement = 40 ± 3
Fadeout Energy = 14 ± 1 MeV

T. Santhosh et. al. Phys Lett B 841 (2023) 137934

Experimental (open squares) and Shell Model Monte Carlo (solid squares) level densities for $^{142-151}$Nd at an excitation energies 2.5, 5 and 7.5 MeV.

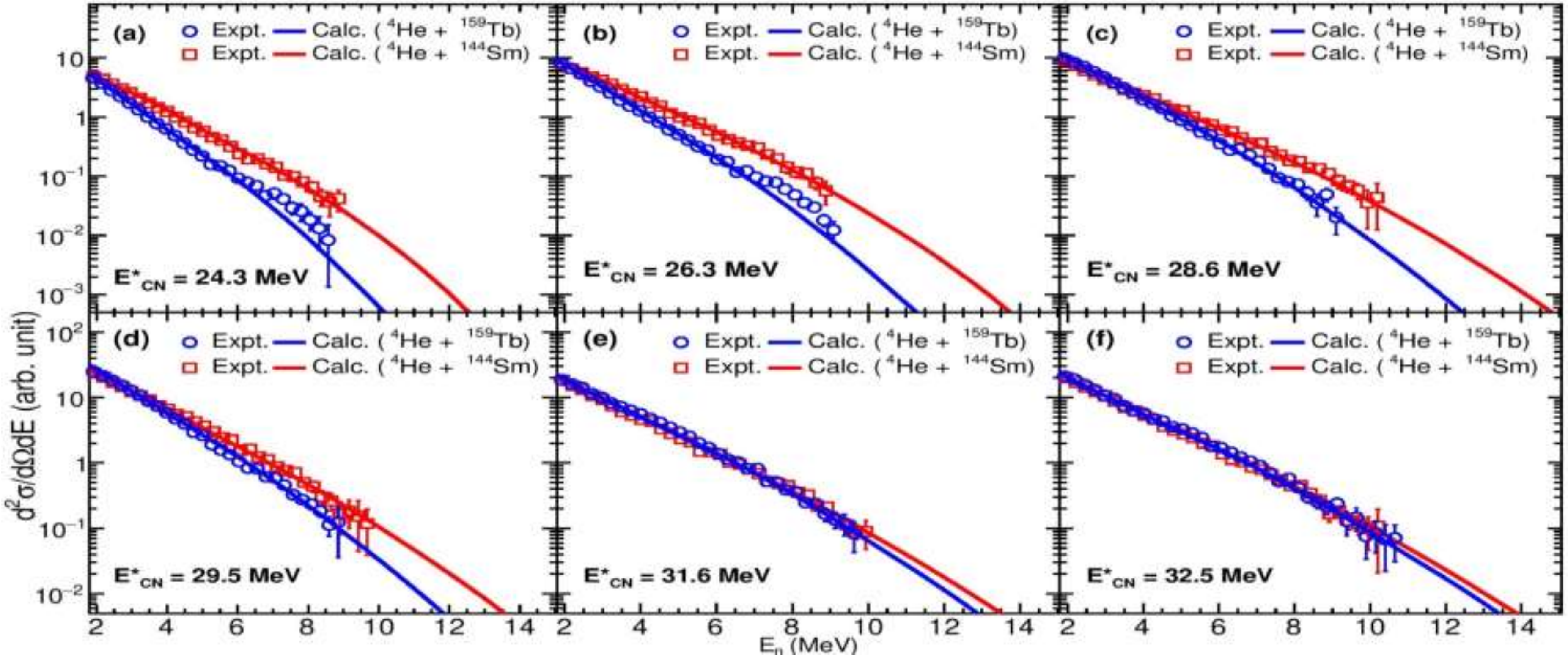
Populated Nucleus	^{142}Nd	^{143}Nd	^{144}Nd	^{145}Nd	^{146}Nd	^{147}Nd	^{148}Nd	^{149}Nd	^{150}Nd	^{151}Nd	^{152}Nd
β_2	0.09	0.11	0.12	0.14	0.15	0.18	0.20	0.25	0.29	0.32	0.35
N-Z	22	23	24	25	26	27	28	29	30	31	32
$Z-Z_0$	1.43	1.42	1.41	1.40	1.39	1.38	1.37	1.37	1.36	1.35	1.34

Guttornsen et. al. Phys Lett B 816 (2021) 136206

Collective enhancement in Ho-isotopes

Reactions:- $^{4}He + {}^{159}Tb \rightarrow {}^{162}Ho + n$

$^{4}He + {}^{144}Sm \rightarrow {}^{147}Gd + n$



- Measured neutron energy spectra were compared with statistical BSFG model calculation using TALYS-v1.96.
- Inverse level density parameter (k = 1/α) was tuned to fit the measured spectra.
- In $^{4}He + {}^{159}Tb$, parameter α changes from 0.120 MeV^{-1} to 0.083 MeV^{-1} with the change in excitation energy.

Method I

$$\rho(E^*, J) = \rho_{int}(E^*, J) K_{Coll}(E^*)$$

$$K_{rot}(E^*) = [\sigma_\perp^2 - 1] f(E^*) + 1$$

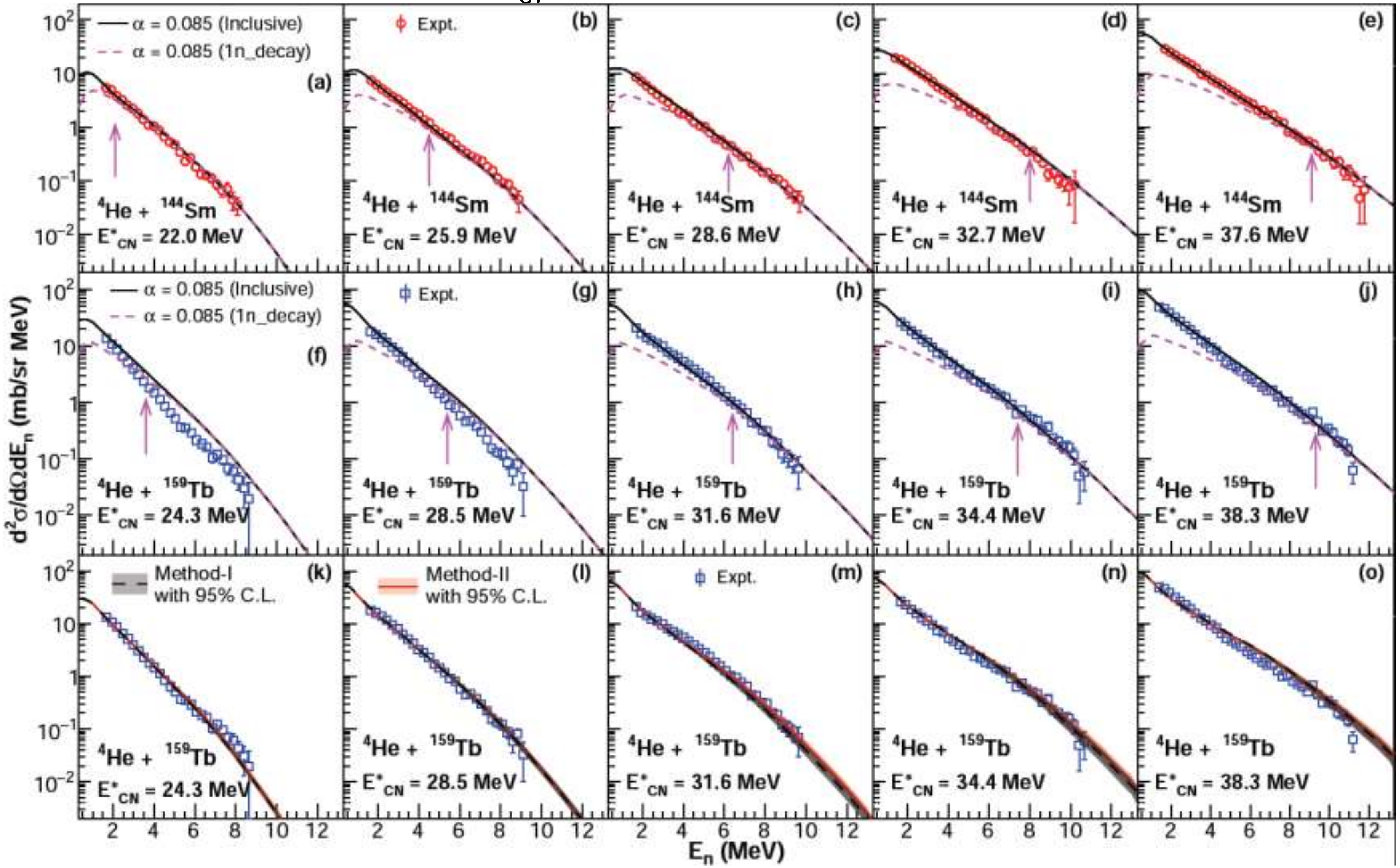
$$K_{vib}(E^*) = [K_{LDM} - 1] f(E^*) + 1$$

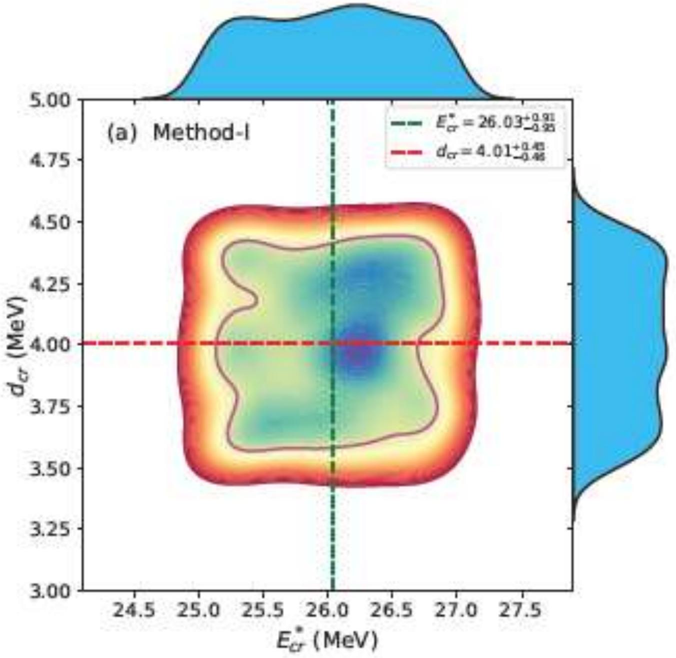
$$f(E^*) = \frac{1}{1 + \exp \frac{[(E^* - E^*_{Cr})]}{d_{Cr}}}$$

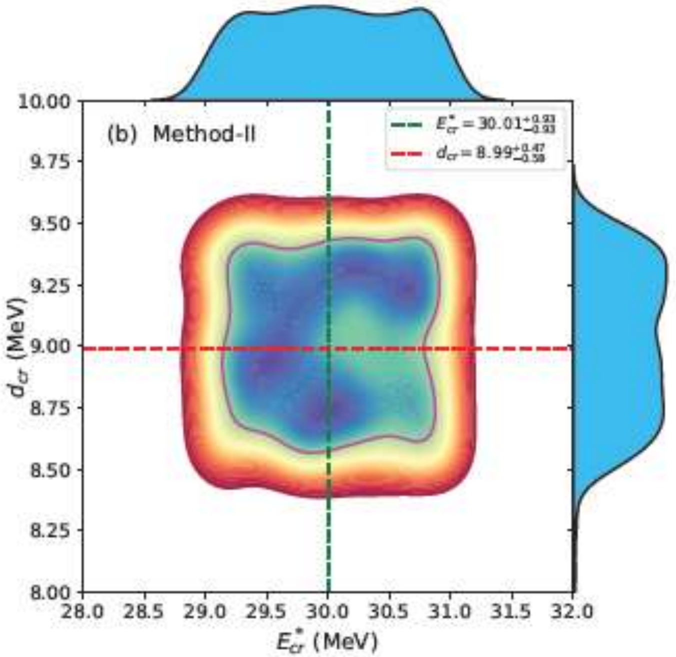
Method II

$$K_{Coll} = 1$$

$$\alpha(E^*) = \alpha_0 f(E^*) + \alpha_1 [1 - f(E^*)]$$







$$\rho_{exp}(E^*) = \rho_{model}(E^*)\frac{(d\sigma/dE_n)_{exp}}{(d\sigma/dE_n)_{model}}$$

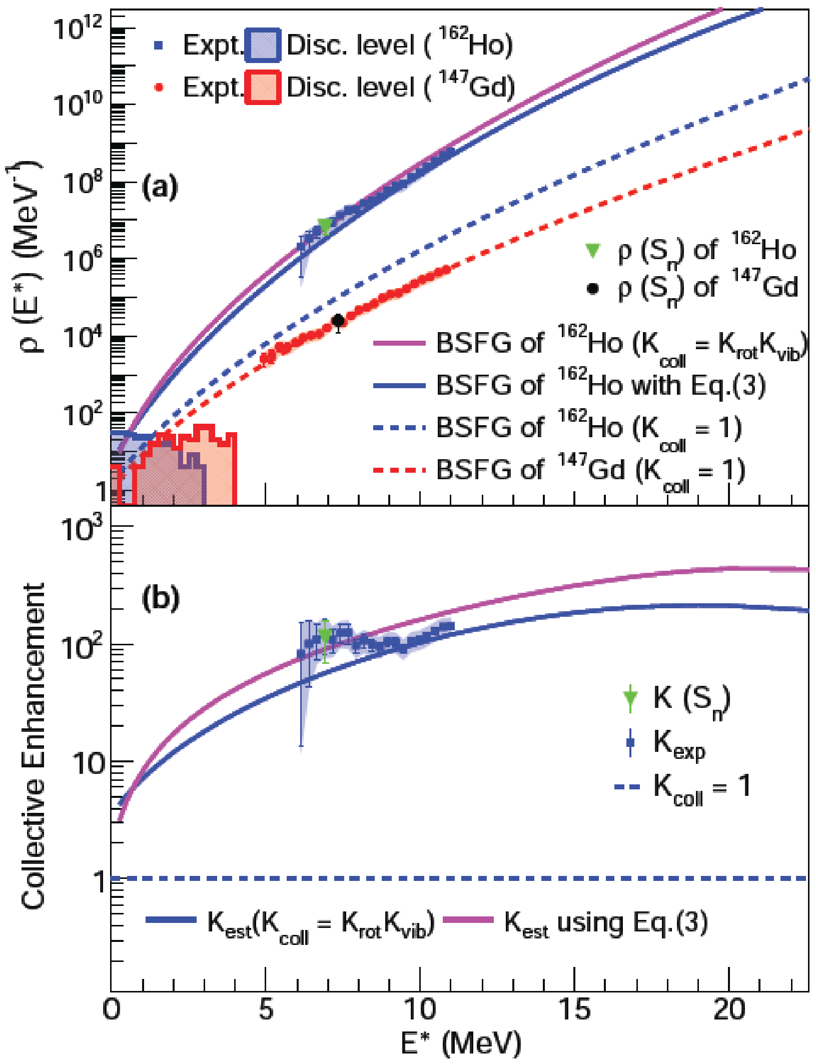
Here, $E^* = E^*_{CN} - S^P_n - E_R - E_n$

S^p_n → **Neutron separation energy of CN.**

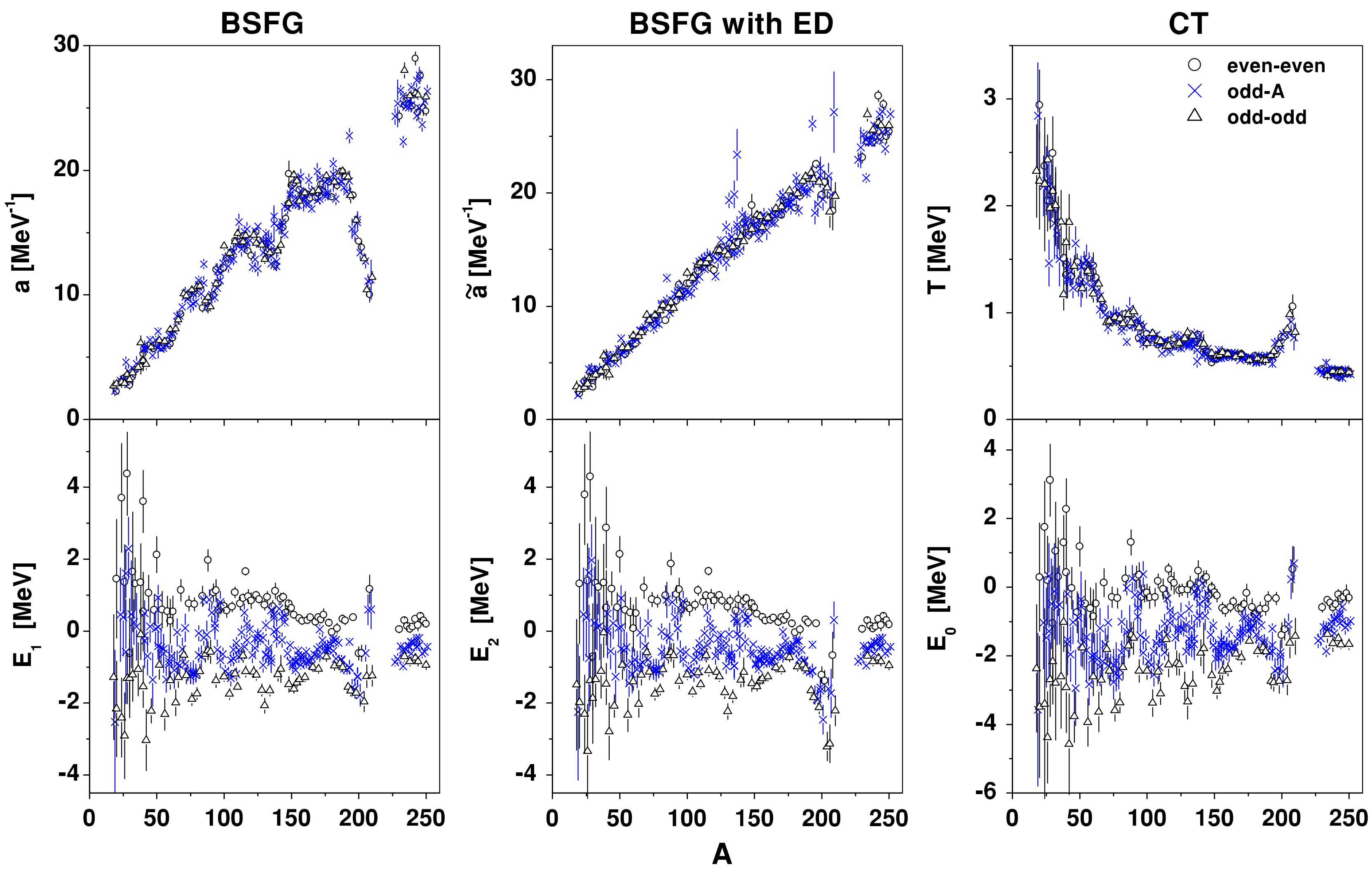
E_R → **Rotational kinetic energy.**

E_n → **Neutron kinetic energy.**

- **Collective Enhancement factor is determined using –**
  - $K_{exp} = \rho_{exp}(E^*) / \rho_{SP}(E^*)$
- **Collective Enhancement factor for ^{162}Ho is found to be 114 +/- 43**



Global parametrization of NLD parameters

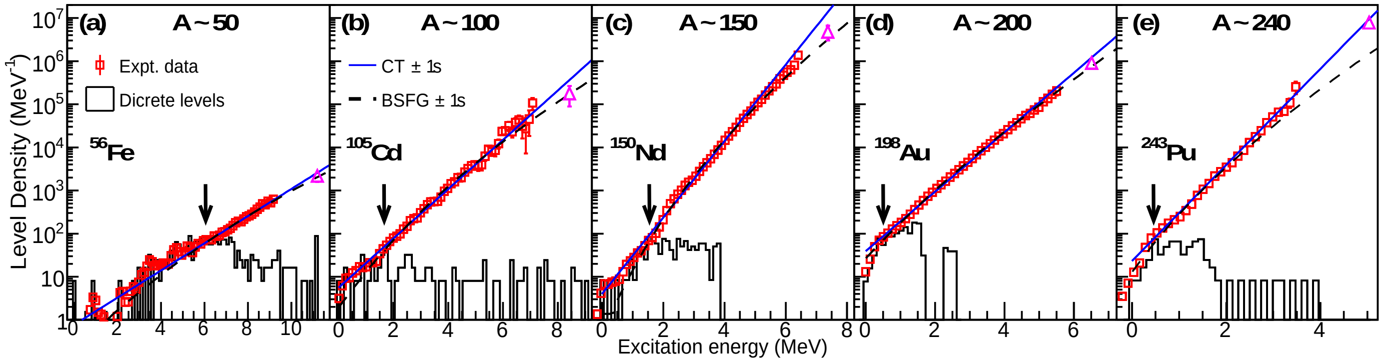


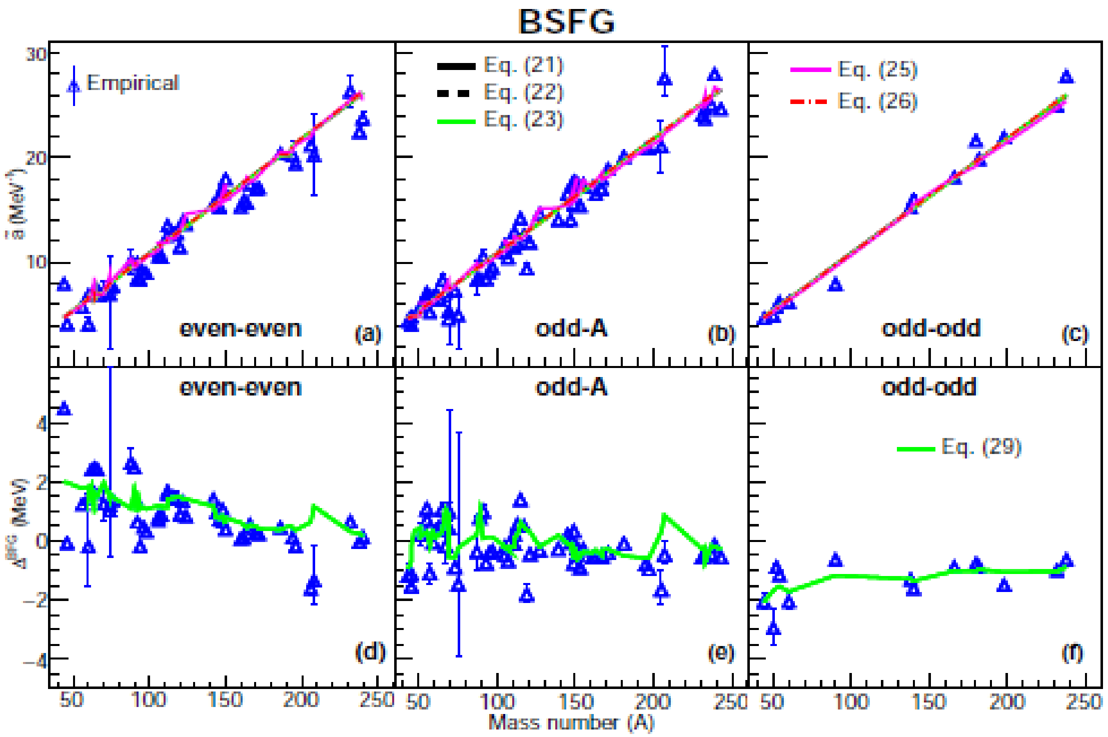
Excitation Energy ~ 8MeV

T. Von Egidy and E. Bucurescu Phys Rev C 72, 044311 (2005)

Global fitting using Bayesian optimization method to determined NLD parameters, a and Δ^{BFG}

NLDs from OSLO and fusion evaporation method was used to determine the NLD parameter a and Δ^{BFG} of the individual nucleus. These parameters were then plotted as a function of mass number A





$$\tilde{a} = p_1 A, \tag{21}$$

$$\tilde{a} = p_1 A + p_2 A^{2/3}, \tag{22}$$

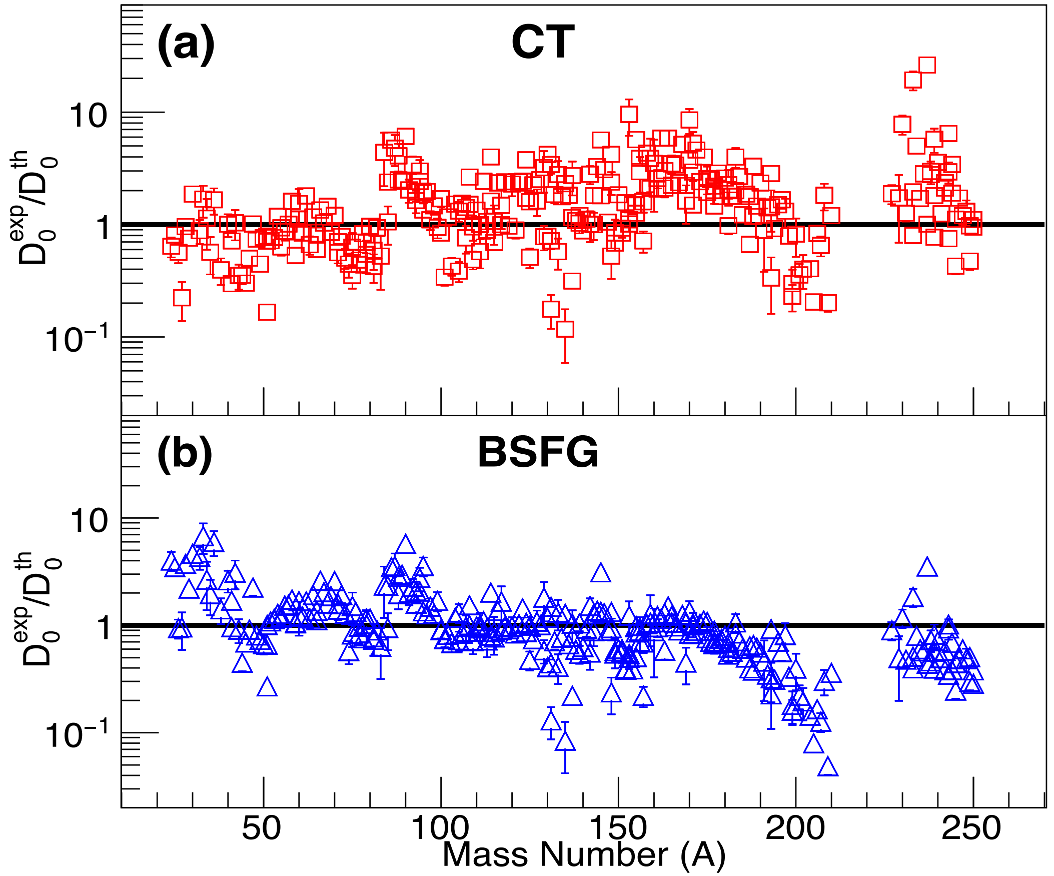
$$\tilde{a} = p_1 A + p_2 B_s A^{2/3} + p_3 B_k A^{1/3}. \tag{23}$$

$$\tilde{a} = p_1 A / exp[p_2 (Z - Z_0)^2]. \tag{25}$$

$$\tilde{a} = p_1 A + p_2 A^2. \tag{26}$$

$$\begin{aligned} \Delta^{BFG} &= \frac{12}{\sqrt{A}} + (p_1 + 0.5 P_d), && \text{e-e} \\ &= \frac{6}{\sqrt{A}} + (p_1 + P_d), && \text{o-e,e-o} \\ &= (p_1 + 0.5 P_d). && \text{o-o} \end{aligned} \tag{29}$$

Validated using experimental D_0 values from RIPL3



Available experimental NLD from fusion evaporation method

Mass region	Reference
^{44}Sc	PRC 77 (2008) 034613
^{47}Ti	PRC 77 (2008) 034613
^{52,54}Mn	PRC 92 (2015) 014303
^{55,57}Fe	PRC 92 (2015) 014303
^{55,57}Co	PRC 92 (2015) 014303
^{59,60,61,62,63,64}Ni	EPJ Web of Conf. 21 (2012) 05001
^{61,67}Zn	PLB 859(2024)139101
^{74,76}Ge	PRC 99 (2019) 054609
^{60,64,66}Zn	PRC 88 (2013) 064324, PRC 103 (2021) 015802
^{90}Zr	PRC 90 (2014) 044303
^{96}Tc	PRC 96 (2017) 054326
^{115,119,127}Te	PLB 831 (2022) 137145

Mass region	Reference
^{171}Yb	PLB 841 (2023) 137934
^{184}Re	PLB 789 (2019) 634
^{200}Tl	PLB 789 (2019) 634
^{211}Po	PLB 789 (2019) 634
^{212}At	PLB 789 (2019) 634

Summary and Outlook

The backward-angle neutron evaporation spectrum from (p,n) and (^{4}He,n) reactions can be utilized to determine nuclear level densities (NLD) above 8 MeV.

This would aid in benchmarking the calculated nuclear level densities (NLDs) from both microscopic and phenomenological models. It would also be valuable for nuclear reaction codes used to predict (n,n') and (n,2n) reactions.

Experimental Plan
Investigate the role of collective enhancement and its fadeout energy in Gd and Hg isotopes

Compilation and evaluation work
Compilation and evaluation of NLD from fusion evaporation reaction in the mass region $110 \leq A \leq 170$

Collaborators

P. Roy, P. Pant, R. Shil, A. Chakraborty, S. Kundu, T. K. Rana, T. K. Ghosh, G. Mukherjee, R. Pandey, A. Sen, S. Manna, J. Sadhukhan

Thank You