EPJ Web of Conferences **322**, 06002 (2025) https://doi.org/10.1051/epjconf/202532206002
*CNR*24*

Comparing Nuclear Level Densities: Particle Evaporation vs Neutron Resonance Data

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Abstract. A systematic evaluation of experimental data consistency was conducted, incorporating s-wave and p-wave resonance spacings and particle evaporation techniques. This analysis highlights the importance of integrating multi-technique data to improve theoretical understanding and constrain level density models for practical applications.

1 Introduction

Nuclear level density is one of the most uncertain inputs in modern reaction codes, which are crucial for applications such as data evaluations, astrophysics, and neutron interrogations. Different level density models can result in variations of a factor of three or more in reaction cross-section calculations [1]. To reduce these uncertainties in reaction modeling, particularly those related to level density models, it is essential to identify the sources of these uncertainties and develop methods to mitigate them.

The parameters of level density models in reaction codes are primarily constrained by experimental data on s-wave neutron resonance spacings. However, these spacings are limited to a narrow spin and energy range. Furthermore, systematic uncertainties in neutron resonance spacings arise from evaluation procedures, particularly those accounting for missing resonances and difficulties in distinguishing s-wave and p-wave resonances. To more accurately constrain level density models, it is essential to supplement neutron s-wave resonance spacings with other types of data.

Nuclear reaction codes employ level density models to calculate cross sections. When a reaction goes through the compound mechanism, cross sections are primarily determined by the level densities of the nuclei populated during the reaction. Consequently, compound nuclear reactions provide a natural means to study level densities

This presentation analyzes and compares two complementary datasets to s-wave resonance spacings: p-wave resonance data from the RIPL database [2] and level densities derived from compound nuclear reactions via the particle evaporation technique. By examining the discrepancies between these datasets, we aim to identify the underlying causes and ultimately refine level density models.

2 Comparison of s- and p-wave neutron resonances spacings

P-wave resonance spacing data has traditionally been omitted from level density model parameterization due to perceived higher uncertainties. These uncertainties stems from the increased challenges in analyzing weaker p-wave resonances compared to their stronger s-wave counterparts. Despite the challenges, p-wave resonance spacing data are available [2] . It is intriguing to examine the consistency of these data with level density models parameterized solely from s-wave resonance spacing data. Discovering systematic differences would provide valuable insights for refining level density model parameterizations, ensuring compatibility with both s-wave and p-wave resonance data.

For the analysis, the Fermi-gas model [3] for the total level density is used in the form:

$$\rho(E) = \frac{\exp(2\sqrt{a(E-\delta)})}{12\sqrt{2}\sigma a^{1/4}(E-\delta)^{5/4}},$$
$$\sigma^2(E) = 0.0138 \cdot A^{5/3}\sqrt{(E-\delta)\cdot a(E)}/\tilde{a}. \qquad (1)$$

where a, $\tilde{a}$ and δ are model parameters [2]. The s- and p-wave resonance spacings $\mathrm{D}_0, \mathrm{D}_1$ at the neutron separation energy $\mathrm{S_n}$ is calculated as

$$D_{0(1)} = \frac{2}{\rho(S_n)\times\sum_J g(J)},$$
$$g(Sn,J) = (2J+1)/(2.*\sigma^2(S_n))\times$$
$$\exp(-(J+0.5)^2/(2.*\sigma^2(S_n))), \qquad (2)$$

where J = I − 1/2 + n, where $n = 0,1$ for D_0 and $n = -1,0,1,2$ for D_1, providing that J ≥ 0. The factor 2 in the nominator assumes an equal number of positive and negative parity resonances. To compare the compatibility of the level density model parameters for s- and p-wave resonances, the parameters a and δ in Eq.1 were adjusted to reproduce the s-wave resonance spacings D_0 from Ref.[2]. These adjusted parameters were then used

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to calculate the p-wave resonance spacings D_1. The ratios of the calculated to experimental values for both s-wave and p-wave resonances are shown in Fig.1. Although individual data uncertainties were not propagated, the results appear to indicate a systematic overestimation of the D_1 model value compared to experimental ones in the mass range up to 100. This means that calculated density of p-wave resonances are underestimated by the model adjusted to reproduce D_0. This result suggests two possible explanation: the first one is that analysis of experimental p-wave resonance systematically underestimate number of p-wave resonances, due to either miss-assignment of the orbital momentum to observed resonances; the second reason is that the model does not adequately reproduce the spin and/or parity distribution of levels at the neutron separation energy. In fact, the model of Eqs. (1),(2) assumes a simple spin distribution and equal number of positive and negative parity levels that might not be supported by more sophisticated microscopical models, especially for light nuclei in the region of $A \lessapprox 60$. Since D_0 and D_1 involves resonances with different parities, the simple model above might not work for both of them simultaneously.

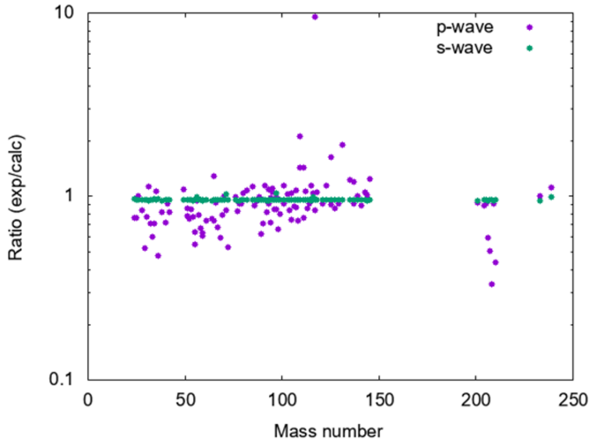

Figure 1. Ratio of experimental and calculated resonance spacings. Fermi-gas LD parameters are adjusted to reproduce s-wave (D_0) resonance spacing

3 Particle evaporation

The level density can also be studied experimentally using a technique that analyzes differential cross sections of outgoing particles from compound nuclear reactions [4]. All experimental results presented here were obtained at the Edwards Accelerator Lab, Ohio University, using a tandem 4.5 MV electrostatic accelerator and different beam species. To detect charged particle ejectiles, we used a charged particle spectrometer, which consists of time-of-flight arms and a $\Delta E - E$ telescope, all equipped with silicon detectors. To measure neutron spectra, we used the Swinger neutron facility, which consists of the swinger magnet and the time-of-flight underground tunnel, allowing high-precision measurements in low-background conditions. The level density obtained from the particle evaporation technique allows for the exploration of broader spin and excitation energy ranges compared to neutron resonance data. This method encompasses excitation energies from the ground state up to the neutron separation energy and includes a significant fraction of possible spin states. However, this technique may introduce uncertainties related to contributions from non-compound reaction mechanisms. Therefore, it is crucial to compare various approaches to level density studies in order to address systematic uncertainties associated with each method. Core concepts and limitations of both neutron resonance and particle evaporation techniques are summarized in Table 1.

4 Level density comparison

The particle evaporation technique provides an independent measurement of the total level density in the energy region below and at the neutron separation energy, which can be compared to estimates derived from s- and p-wave resonances using Eqs. (1, 2). This comparison has the potential to reveal the consistency between the two techniques and provide insight into the spin distribution (or spin cutoff parameter $\sigma(E)$), as the conversion from the neutron resonance spacing Eq. (2) to the total level density Eq. (1) relies on the spin distribution model of Eq. (2).

In order to get absolute level density values, the particle evaporation techniques uses the scaling factor to normalize obtained level density to density of levels known from a discrete level scheme in the low excitation energy region. Theretofore, it is important to measure evaporation spectra including the region of discrete levels populated by emitted particles. Poor statistics in this region results in sizable absolute normalization uncertainties.

Figures below show level densities obtained from the particle evaporation technique along with calculations using the Fermi-gas model (1) with parameters adjusted to match experimental values of D_0, D_1 at the neutron separation energy and to reproduce the density of discrete levels at low excitation energies. Nuclei were chosen based on the availability of comprehensive data sets, combining particle evaporation and neutron resonance information, sourced from existing publications and preliminary experimental results.

We can see a relatively good agreement of level densities obtained from evaporation technique and those estimated using both s-wave and p-wave neutron resonance spacings for ^{57}Fe,^{59} Ni,^{60} Ni. The level density for ^{55}Fe obtained from evaporation technique appears to be in a closer agreement with estimates based on the s-wave resonance spacing D_0, however, possible uncertainties for the absolute level density normalization makes such a conclusion uncertain. More distinct level densities estimated from D_0 and D_1 is observed for ^{32}P, and the level density from evaporation technique appears to be in a closer agreement with the level density estimated from the D_1 value. Even larger difference between the Fermi-gas model parameterized on D_0 and D_1 values is observed for ^{36}Cl, and the level density obtained from the particle evaporation spectrum is in a closer agreement with estimates based on D_1 values.

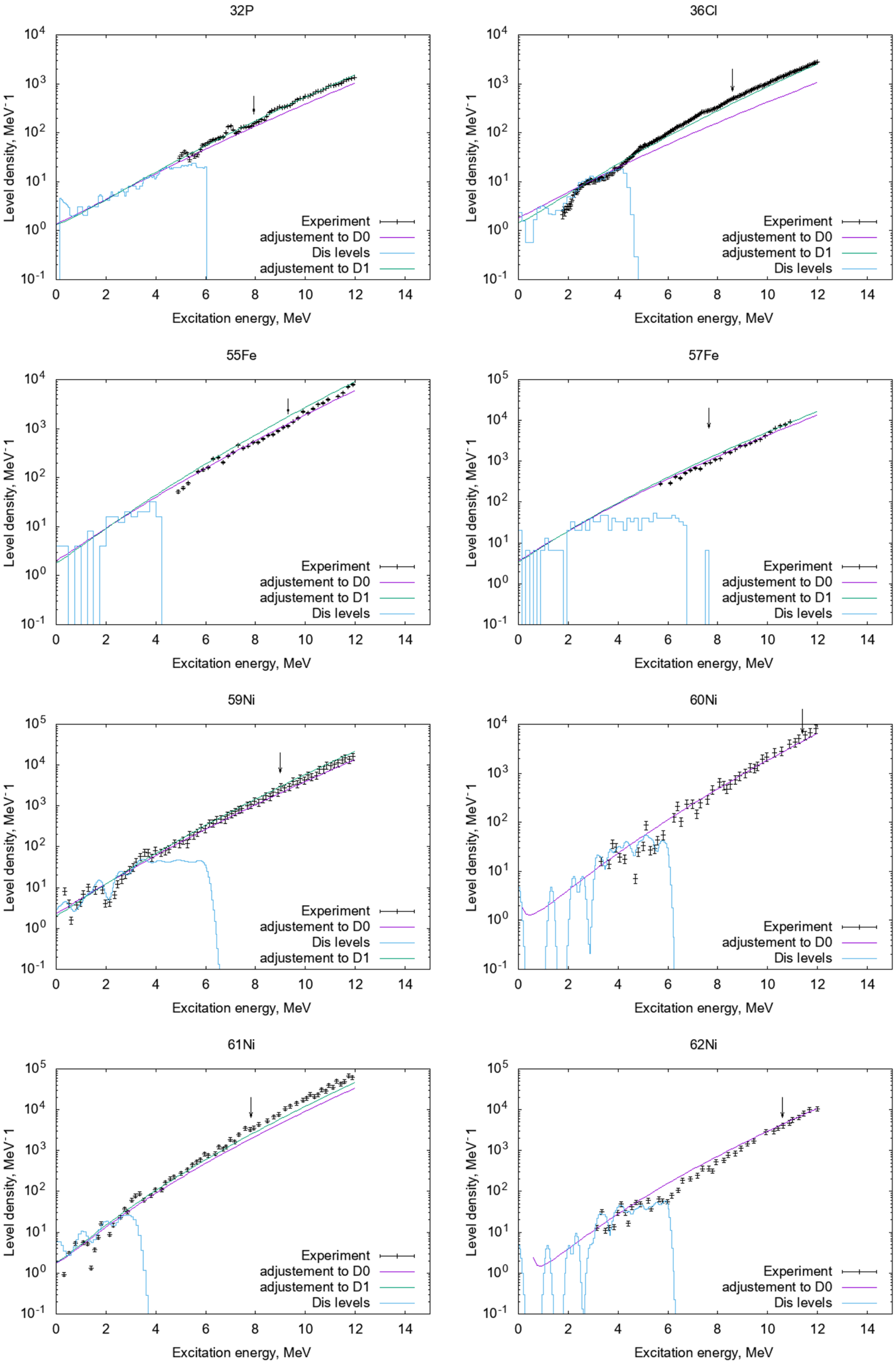

Figure 2. Level densities obtained from the particle evaporation technique (points), from know level scheme (discrete levels) and from Fermi-gas model adjusted to reproduce s-wave (D_0) and p-wave (D_1) neutron resonance spacings. Arrows correspond to the neutron separation energy S_n.

Table 1. Comparison of neutron resonance and particle evaporation level density techniques

	Core concept	Limitations
Particle evaporation	Allows studying level densities in a large excitation energy and spin intervals	Might be potentially prone to uncertainties caused by contributions of non-compound reactions
Neutron resonances	Allows precise counting of individual levels at S_n	Potentially prone to uncertainties caused by missing resonances, miss-identifying s- versus p-wave resonances. Resonances are measured in restricted excitation energy and spin intervals

A relatively good agreement is observed between level densities derived from the evaporation technique and those estimated using both s-wave and p-wave neutron resonance spacings for ^{57}Fe,^{59}Ni, and ^{60}Ni. However, for ^{55}Fe the evaporation technique yields level densities closer to estimates based on s-wave resonance spacing (D_0), although uncertainties in absolute level density normalization render this conclusion uncertain. More pronounced differences between D_0 and D_1-based level densities are seen for ^{32}P, with the evaporation technique aligning more closely with D_1 -estimated level densities. An even larger discrepancy between Fermi-gas model parameterizations using D_0 and D_1 values is observed for ^{36}Cl, with evaporation-spectrum-derived level densities showing better agreement with D_1-based estimates.

5 Conclusion

The comparison of level densities derived from s-wave D_0 and p-wave D_1 (D resonances, and particle evaporation spectra, reveals nucleus-dependent variations. This highlights the significance of incorporating experimental data from diverse techniques to refine existing level density models for practical applications.

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