Nuclear Level Density and γ-ray Strength Function of $^{63}$Ni

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The nuclear level density (NLD) and γ-ray strength function (γSF) of $^{63}$Ni have been investigated using the Oslo method. The extracted NLD is compared with previous measurements using particle evaporation [1] and those found from neutron resonance spacing [2–4]. The γSF was found to feature a strong low energy enhancement that could be explained as M1 strength based on large scale shell model calculations [5]. Comparison of γSFs measured with the Oslo method for various Ni isotopes reveals systematic changes to the strength below 5 MeV with increasing mass.

I. INTRODUCTION

The Oslo method is a powerful analytical method that allows for simultaneous extraction of nuclear level density (NLD) and γ-ray strength functions (γSF) from particle-γ coincidences following reactions with light ion beams (e.g. $(p, p')$, $(d, p)$ etc.) [6]. The method has been extended to be used in conjunction with total absorption spectrometry following β-decay (β-Oslo method) [7] and particle-γ coincidences from inverse-kinematics experiments [8].

The Oslo method itself does not provide the absolute NLD and γSF values, but rather the functional shapes. In order to determine the correct common slope of the NLD and γSF, as well as their absolute values, a normalization to auxiliary experimental data is required. Typical data for normalization are the s-wave resonance spacings, discrete resolved levels and average radiative width.

The reliance on external data means that the accuracy of the final NLD and γSF is mostly determined by the accuracy of those data. The resonance spacings and radiative widths can be highly uncertain, especially in nuclei with few resonances. For the majority of unstable nuclei these have not even been measured. This means that alternative approaches for normalization have to be used especially for cases where no experimental resonance data are available. For nuclei close to stability these values can typically be estimated from systematics in the vicinity of the nucleus using models [7]. The down side of such normalized NLDs and γSFs is the introduction of model dependencies which may result in large uncertainties. A model independent approach is the use of the Shape method [9, 10] to determine the slope of the γSF, however the method requires sufficient particle energy resolution and a well known level structure with resolvable energy spacing at low excitation energy. In this paper we will look at a possible third option in which only NLD from known discrete states is used to normalize the NLD.

II. EXPERIMENT AND ANALYSIS

The experiment measuring particle-γ coincidences from the $^{14}$Ni($p, d$)$^{63}$Ni reaction was performed with a 27.4 MeV proton beam accelerated by the Separated Sector Cyclotron (SSC) at iThemba LABS. The 4.56 mg/cm$^2$ thick $^{64}$Ni target was bombarded with a beam current of ≈ 1 pnA for about 15 hours at the center of the AFRODITE array [19]. The array consisted of eight Compton suppressed high purity germanium (HPGe) CLOVER detectors, six small (2”x2”) and two large volume (3.5”x8”) LaBr$_3$:Ce detectors. Particles from the reaction were measured by two silicon detectors of the S2 type in a ∆E-E configuration and placed down stream of the target. The ∆E detector had a thickness of 309 μm and the E detector was 1041 μm thick. In front of the particle telescope a 10 μm thick aluminum absorber was placed to shield from δ-electrons. Signals from the detectors were read out using Pixie-16 digital pulse processors from XIA. Each detector was self-triggering and the pulse height, timestamp and constant fraction correct-
tions of each event were stored to disk for offline analysis.

Particle-γ coincidences were found in the list mode data by placing time gates on the prompt time peak in the particle-γ time spectra. Background events were found by placing an off-prompt time gate of similar length. The mass and charge of the ejected particle, and thus the reaction channel, was selected by applying a graphical cut in the ΔE vs. E matrix. For each event the excitation energy of the residual $^{63}$Ni nucleus was found from kinematic reconstruction assuming a two-body reaction. The resulting excitation energy and coincident γ-ray spectrum were then used to construct the prompt excitation versus γ-ray energy matrix shown in Fig. 1(a). A similar background excitation-γ-ray energy matrix was constructed from the events in the background time gate. After applying time and particle gates a total of $3.7 \times 10^6$, $4.8 \times 10^6$, and $5.7 \times 10^6$ prompt particle-γ coincidences and $7.3 \times 10^5$, $1.0 \times 10^6$ and $7.9 \times 10^5$ background events were found in the CLOVER, large LaBr$_3$:Ce and small LaBr$_3$:Ce detectors, respectively. The considerably lower background to prompt ratio for the small LaBr$_3$:Ce detectors can be attributed to their exceptionally high time resolution [20]. In the following analysis only particle-γ coincidences in the large LaBr$_3$:Ce detectors were considered as these exhibit far superior efficiency at high γ-ray energies which is important in the Oslo method.

### A. The Oslo method

The starting point for the Oslo method is the excitation-γ matrix. The first step is to correct for the response of the γ-detector using the unfolding method [21]. The response function of the setup was found from simulations of the AFRODITE array using a model implemented in Geant4 [22, 23]. The resulting unfolded matrix is shown in Fig. 1(b). The peak at $E_x = 3.6 \text{ MeV}$ to the ground state was fitted and subtracted from the unfolded spectra with the justification being that this state is only populated directly from the reaction and has no feeding from the quasi-continuum.

Next is to find the first generation matrix using the first generation method [24]. The resulting first generation matrix contains the distribution of the first γ-rays emitted in cascades depopulating each excitation bin and is shown in Fig. 1(c).

The first generation matrix is proportional to the NLD and γ-ray transmission coefficient via [6]

$$
\Gamma(E_γ, E_x) \propto T(E_γ)\rho(E_x - E_γ),
$$

(1)

where $\Gamma(E_γ, E_x)$ is the bin with γ-ray energy $E_γ$ and excitation energy $E_x$. $T(E_γ)$ is the transmission coefficient for γ-ray energy $E_γ$ and $\rho(E_x - E_γ)$ is the level density at the final excitation energy $E_f = E_x - E_γ$. The NLD and γ-ray transmission coefficients are extracted from the first generation matrix by fitting a theoretical matrix

$$
\Gamma_{th}(E_γ, E_x) = \frac{\rho(E_x - E_γ)T(E_γ)}{\sum_{E_γ=E_{γ,min}}^{E_γ=E_{γ,max}} \rho(E_x - E_γ)T(E_γ)},
$$

(2)

where $\rho(E_x - E_γ)$ and $T(E_γ)$ are treated as free variables for each final energy $E_f = E_x - E_γ$ and γ-ray energy $E_γ$. The fit was done by minimizing

$$
\chi^2 = \sum_{E_x, E_γ} \frac{(\Gamma(E_γ, E_x) - \Gamma_{th}(E_γ, E_x))^2}{\Delta\Gamma(E_γ, E_x)}.
$$

(3)

The region of the first generation matrix fitted was limited to a minimum γ-ray energy of 1500 keV and excitation energies between 3100 keV and 6600 keV to ensure only statistical decay was included. The region is highlighted by the dashed line in Fig. 1(c).

The resulting theoretical first generation matrix are shown for a few select excitation bins together with the experimental matrix in Fig. 2.

The NLD and γ-ray transmission coefficients resulting from the $\chi^2$ minimization are not the physical values, but rather the shape as Eq. (3) is symmetric under transformation

$$
\tilde{\rho}(E_x - E_γ) = A\rho(E_x - E_γ)e^{\alpha(E_x - E_γ)}
$$

$$
\tilde{T}(E_γ) = B T(E_γ) e^{\alpha E_γ},
$$

(4)

where $A$, $B$ and $\alpha$ are transformation parameters. To obtain the physical transformation for the extracted NLD and γ-transmission coefficients, a normalization to external data has to be performed, see Sect. III. The γ-ray transmission coefficient is related to the transmission coefficient via $f(E_γ) = \tilde{T}(E_γ)/(2\pi E_γ^2)$, under the assumption that dipole transitions dominate the transmission coefficients.

### III. NORMALIZATION OF LEVEL DENSITY & Γ-RAY STRENGTH FUNCTION

The main auxiliary data required to normalize the NLD is known level densities from tabulated levels and the NLD at the neutron separation energy $S_n$. Tabulated levels are converted to level density simply by counting the number of levels within each excitation bin and dividing by the bin width. This results in a level density that will have large fluctuations compared to Oslo method data as the experimental resolution has not yet been accounted for. The level density from known levels is smoothed with a Gaussian with FWHM of about 325 keV to match the experimental resolution for final excitation energy. Tabulated discrete levels were taken from the RIPL-3 library [3].

The level density at the neutron separation energy is found from the resonance spacing of s-wave resonances $D_0$ by [6]

$$
\rho(S_n) = \frac{2}{g(S_n, J = 1/2) + g(S_n, J = 3/2)} \frac{1}{D_0},
$$

(5)
with the spin-cutoff parameter parameterized by \cite{26}

\[ \sigma^2(E_x) = \begin{cases} \sigma_d^2, & E < E_d \\ \frac{\sigma_d^2}{S_n} + \frac{E - E_d}{S_n} (\sigma(S_n) - \sigma_d^2), & E \geq E_d. \end{cases} \]  

(7)

The spin-cutoff parameter of the discrete levels \(E_d = 2.0\) MeV is estimated to be \(\sigma_d = 2.30(23)\) from tabulated discrete levels \[3\] and large scale shell model calculations \[5\], while the spin-cutoff parameter at the neutron separation energy was estimated to be \(\sigma(S_n) = 3.68(21)\) estimated from the models of refs. \[27\], \[28\] and \[29\]. The s-wave resonance spacing \(D_0 = 16.0(30)\) keV was taken from the RIPL-3 database \[3\] resulting in a total level density at the neutron separation energy of 1730(363) MeV\(^{-1}\).

The experimental NLD only extends up to 5.2 MeV and to properly compare with the level density at the neutron separation energy the NLD is extrapolated to \(S_n\) via a constant temperature (CT) formula \cite{25}

\[ \rho_{\text{CT}}(E_x) = \frac{1}{T} \exp \left( \frac{E_x - E_{\text{shift}}}{T} \right), \]  

(8)

where the temperature \(T\) and shift parameter \(E_{\text{shift}}\) are treated as free parameters.

Data required to normalize the \(\gamma\)SF is the average radiative width of s-wave resonances, as this value is related to the \(\gamma\)SF and NLD via \cite{30}

\[ \langle \Gamma_{\gamma 0} \rangle = \frac{D_0}{2} \int_0^{S_n} dE_\gamma E_\gamma^2 f(E_\gamma) \rho(S_n - E_\gamma) \times \left[ g(S_n - E_\gamma, 1/2) + g(S_n - E_\gamma, 3/2) \right] E_\gamma. \]  

(9)
TABLE I. List of parameters used to normalize the NLD and γSF. The spin-cut at $S_n$ and $\gamma SF$ are estimated from the model predictions of [27], [28] and [29] while the discrete levels spin-cut is estimated from the discrete states [3] and shell model calculations [5]. The $s$-wave resonance spacing $D_0$ are taken from [3], while the $\langle \Gamma_{\gamma} \rangle$ is a weighted average of tabulated radiative widths in [3].

| Parameter          | Value               |
|--------------------|---------------------|
| $S_n$              | 6.838 MeV           |
| $D_0$              | 16.0(30) keV        |
| $\sigma(S_n)$      | 3.63(21) MeV        |
| $E_d$              | 2.0 MeV             |
| $\sigma(E_d)$      | 2.3(23) MeV         |
| $\langle \Gamma_{\gamma} \rangle$ | 534(214) meV |
| $\rho(S_n)$        | 1730(363) 1/MeV     |

Due to the limits selected (see Sect. [1A] for the extraction of the NLD and $\gamma SF$ the experimental data only extends up to $E_x = 5.2$ MeV and $E_\gamma$ between 1.5 and 6.6 MeV, respectively. To evaluate the integral in eq. (9) the NLD was extrapolated with the constant temperature formula, eq. (8), between 0 and 1.5 MeV and the neutron separation energy. The $\gamma SF$ was extrapolated using $f(E_\gamma) = CE^{\gamma E}$, and $f(E_\gamma) = CE^{\gamma E}/E_\gamma$ for energies between 0 and 1.5 MeV, and 6.6 MeV and the neutron separation energy, respectively. The average radiative width of $s$-wave resonances in $^{63}$Ni was found to be 534(214) meV by a weighted average of all the tabulated values found in [3]. Due to the large spread of the tabulated values a large uncertainty of 40% was assumed. All normalization parameters adopted in this analysis are listed in Table [3]. The normalization parameters $A$, $B$ and $\alpha$ were found by sampling the posterior probability distribution with total likelihood function

$$\mathcal{L}(\theta) = \prod_i \mathcal{L}_i(\theta).$$

using the Bayesian sampling package UltraNest [31]. All experimental data are assumed to be normally distributed, giving the likelihoods

$$\ln \mathcal{L}_{\text{discrete}} = \sum_i \ln \frac{1}{\sqrt{2\pi \sigma_{j,Oso}(\theta)}} \cdot \left(\frac{\rho_{j,\text{discrete}} - \rho_{j,Oso}(\theta)}{\sigma_{j,Oso}(\theta)}\right)^2,$$

$$\ln \mathcal{L}_{\text{CT}} = \sum_i \ln \frac{1}{\sqrt{2\pi \sigma_{j,Oso}(\theta)}} \cdot \left(\frac{\rho_{j,\text{CT}} - \rho_{j,Oso}(\theta)}{\sigma_{j,Oso}(\theta)}\right)^2,$$

$$\ln \mathcal{L}_{\rho_{S_n}} = \left(\frac{\rho_{S_n} - \rho_{S_n,\text{CT}}(\theta)}{\sigma_{\rho_{S_n}}}\right)^2,$$

$$\ln \mathcal{L}_{\langle \Gamma_{\gamma} \rangle} = \left(\frac{\langle \Gamma_{\gamma} \rangle_{\text{exp}} - \langle \Gamma_{\gamma} \rangle_{\text{Oso}}(\theta)}{\sigma_{\langle \Gamma_{\gamma} \rangle_{\text{exp}}}}\right)^2.$$

The parameters $\theta = (A, B, \alpha, T, E_{\text{shift}}, \sigma_D, \sigma_{S_n})$ have a uniform prior between 0 and 5 for $A$ and $B$ and $-1$ MeV$^{-1}$ and 1 MeV$^{-1}$ for $\alpha$. The temperature and shift parameters also used a uniform prior between 0.2 and 2 MeV and $-10$ and 10 MeV, respectively. The spin cut-off parameters were included as nuance parameters with normal distributed priors to ensure proper propagation of errors. The resulting normalized NLD and $\gamma SF$ are shown as red circles in figs. 3 and 4, respectively. The discrete likelihood, eq. (11) was limited to data points between 2 and 2.7 MeV, while the CT formula was fitted between 3.2 and 4.7 MeV. To investigate the sensitivity to the resonance spacing the analysis was repeated, but excluding Eq. (13) in the total likelihood and resulted in the NLD and $\gamma SF$ shown as blue circles in Fig. 3 and 4, respectively.

**IV. DISCUSSION AND COMPARISON**

**Level density**

We find that the experimental NLD fits exceptionally well with the tabulated discrete NLD up to about
FIG. 4. Extracted γSF when including the NLD at $S_n$ from resonance spacings in the normalization are shown by the red circles while the blue circles only considers the level density from known levels. The orange diamonds are the γSF of $^{61}\text{Ni}$ measured by [14]. The black line shows the calculated M1 strength from shell model calculations [5] considering only decay from levels within the fit region, while the dash-dotted line includes all levels found in the shell model calculation.

$E_x \approx 3.6$ MeV indicating that the level scheme might be complete up to even higher excitation energies, than the evaluated $E_x = 2.7$ MeV [3].

Comparing the two normalizations we see that the one including $\rho(S_n)$ results in a slightly steeper slope. Overall the two normalizations are well within the error-bars of each other demonstrating that normalization without knowledge of the NLD at the neutron separation energy are viable.

Fig. 5 shows the NLD compared with the experimental NLD found from particle evaporation spectra [1] and the NLD found in large scale shell model (SM) calculations [5]. The SM results clearly overestimate the NLD between 1.8 and 3.7 MeV while underestimating above 4 MeV up to around 6 MeV where the model space seems to be exhausted. The NLD found from evaporation studies fits well within the error bars up to about 4.5 MeV where the presented NLD seems to tend to higher densities.

In Fig. 6 the NLDs of $^{59,60,64,65,67,69,70}\text{Ni}$ [12–15, 18] are shown together with the measured $^{63}\text{Ni}$ isotope. We observe a clear trend with the absolute NLD increasingly with mass number while the temperature (i.e. the slope) decreases with mass number.

$\gamma$-ray strength function

The extracted γSF features a strong upbend at low energies similar to what has been seen in other Ni isotopes [12–15, 18], as well as other nuclei in the same mass region [32–34]. Comparing the measured strength function to the M1 strength predicted from the SM calculations in ref. [5] we see that qualitatively these have a similar shape, although the absolute values of the SM calculations are considerably lower. Comparison with the photo-absorption cross section of $^{61}\text{Ni}$ [14] shows a reasonably good agreement as the giant dipole resonance
evolves slowly with mass number. The normalized γSF has a considerably large uncertainty band with the dominating contributing factor being the uncertainty in the average radiative width. Excluding the ρ(Σν) in the normalization does also have a large impact on the uncertainties of the normalization for the γSF, increasing the size of the error bars from ≈ 45% to ≈ 80%, especially at higher γ-ray energies.

In Fig. 7 we show the γSF for $^{59,60,64,65,67,69,70}\text{Ni}$ [12–17] together with the presented γSF. From this comparison we can see a clear trend with the strength below ≈ 4.5 MeV significantly decreasing with higher mass numbers. This is especially apparent in the unstable neutron rich nuclei ($A = 67, 69$ and 70). The outlier are the γSF of $^{65}\text{Ni}$ which have the highest strength overall.

V. SUMMARY

We have measured the NLD and γSF of $^{63}\text{Ni}$ and found that the NLD agrees well with that found from known levels, and are compatible with the NLD at the neutron separation energy found in neutron resonance studies. The NLD of [1] agrees with the presented NLD for excitation energies up to about 4.7 MeV where the presented NLD seems to be somewhat steeper. Based on this we conclude that our results tend to favour the NLD found in resonance studies, rather than those of [1].

The measured γSF features a strong low energy enhancement similar to that found in other Ni isotopes. Shell model calculations from [3] suggests that the enhancement may be due to M1 transitions within the quasi-continuum. Compared with $(\gamma, n)$ [14] data for $^{61}\text{Ni}$ there may be a pygmy resonance around 7-8 MeV, but due to the large uncertainties in the absolute value of the measured γSF we cannot conclude.

In general the exclusion of s-wave spacing in the overall fit of the NLD and γSF resulted in very similar results, although with considerably larger uncertainties when extrapolating towards the neutron separation energy. Based on this we can conclude that if the level scheme is sufficiently well known a reasonably good normalization for the NLD can be obtained even without resonance data.

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