FYS4515 - Oslo Method Project

Julian Ersland Vevik & Tellef Storebakken

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Abstract

This project was done for the FYS4580 - Nuclear Physics-I course at the University of Oslo in the fall 2019. This report will go through how the Oslo Method is used to obtain the gamma-ray strength function (γSF) and nuclear level density (NLD) for the isotope ^{233}Th. The experiment was conducted at the Oslo Cyclotron Lab (OCL) studying the reaction $^{232}\mathrm{Th}(\mathrm{d},\mathrm{p}\gamma)^{233}\mathrm{Th}$. Three articles describing Oslo Method analysis on this experiment was later published [1, 2, 3]. The data used in this report is the same data from this experiment and the resulting γSF and NLD are compared with the already excisting results. An excess in the γSF was found in the region just below $E_\gamma = 2$ MeV. This is recognized as a scissors resonance in the quasicontinuum.

I Introduction

One of the goals of this course was to get an introduction to dynamics in the quasi-continuum region of atomic nuclei, and how the Oslo Method is used to study this.
The Oslo Method is a way of obtaining the nuclear level densities (NLD) and the gamma-ray strength function (γSF). When the γSF and NLD for an isotope are known, they can be used to calculate reaction cross-section for the isotope, among other things.
This report will go through the Oslo Method analysis on the reaction $^{232}\mathrm{Th}(\mathrm{d},\mathrm{p}\gamma)^{233}\mathrm{Th}$.
Section II will go through some of the theory used in the Oslo Method analysis. Section III will go through the Oslo Method analysis done for the given data. In section IV the results from the analysis are shown and in section V they are compared with the existing results from earlier articles mentioned in the abstract. In section VI there are some concluding remarks about the results and comparison.

II Theory

After unfolding the raw spectrum, the Oslo method can be used to find the first-generation matrix. The first-generation matrix $P(E, E_\gamma)$ is proportional to the decay probability to emit a γ-ray of energy E_γ from an initial excitation energy E[2]. Through Fermi's golden rule[4];

$$\lambda_{i\to f} = \frac{2\pi}{\hbar} \left|\langle f|\, H' \,|i\rangle\right|^2 \rho_f, \tag{1}$$

which states that the decay probability $\lambda_{i\to f}$ is given by the transition matrix element and the level density ρ_f at the final state, one can get an expression for $P(E, E_\gamma)$. This can be written as

$$P(E, E_\gamma) \propto \mathscr{T}_{i\to f}\rho_f, \tag{2}$$

where $\mathscr{T}_{i\to f}$ is the γ-ray transmission coefficient and ρ_f is the level density at the excitation energy after the primary γ-ray emission[2]. Using the Brink hypothesis [9], which states that the γ-ray transmission coefficient is approximately inedependent of excitation energy so that only the transition energy E_γ matters, one gets the the simplified expression

$$P(E, E_\gamma) \propto \mathscr{T}(E_\gamma)\rho(E - E_\gamma). \quad (3)$$

This states that one can extract both the level density and γ-ray transmission coefficient simultaneously, which is what was done here with the help of the Oslo method. Furthermore, the $\mathscr{T}(E_\gamma)$ and $\rho(E - E_\gamma)$ functions both need to be normalized. The normalization procedure is described in Ref. [1].

After normalizing the γ-ray transmission coefficient, one can calculate the γSF from

$$f(E_\gamma) = \frac{1}{2\pi}\frac{\mathscr{T}(E_\gamma)}{E_\gamma^3}, \quad (4)$$

where the assumption that the dipole radiation is dominant in the quasicontinuum has been made.

III Data set and analysis

The Oslo Method uses already existing software to go from the raw data obtained in an experiment, to extract the γSF and NLD. One of the programs was the `mama`-program (matrix-massage), which were used for the first two steps described in section III.1.

III.1 "Ten steps to heaven"

The "Ten steps to heaven" is a description of the steps in the Oslo Method, used to go from a raw matrix (from an experiment), to obtain the γSF and NLD.
Usually the "Ten steps to heaven"'s first step is to go from a `root`-matrix to a matrix in the `mama`-format. The matrix studied in this report was already in a `mama`-format so the first step to heaven was not done in this project.

The first step to heaven, was to unfold raw matrix from the experiment. Since the detectors used are not perfect, the obtained gamma-ray spectras from the experiments has a broad energy distribution without outstanding γ-ray lines. The Oslo Method uses a unfolding method described in Ref. [6]. This unfolding method first uses the *folding iteration method* to unfold the matrix. After the first unfolding it uses the *Compton subtraction method* to smooth out the unfolded spectra. Compton-spectra are extracted from the first unfolded spectra and smoothed. After this, the Compton spectra is subtracted from the first unfolded spectra.

The second step was obtaining the first-generation γ-ray spectrum (primary spectrum), using the method described in Ref. [5]. This step is conducted to obtain a spectra where only the primary γ-rays are present, i.e. the first emitted γ-rays from an energy level. Detected γ-ray energies for a given excitation energy includes not only the first generation, but also higher generations of γ-energy transitions. These γ-energy transitions are also present at lower detected excitation energies, which are used to subtract from the γ-ray energies at a higher excitation energy. To avoid losing the whole γ-ray spectrum, the subtracted energies need to be weighted. The weights are decided from the relative branching of each energy level.

In this project, the value subtracted from the γ-ray energy spectras, were normalized using *multiplicity normalization* described in Ref. [5].

The next step was to extract the level density and the γSF from the first generation matrix [7]. The values input to the `rhosigchi.f` program is shown in table 1. These limits were decided by looking at the first generation spectrum (see also figure 3c where the limits are outlined) and deciding the limits so:

- The upper limit of the E_x fulfills the requirement of compund decay
- The lower limit of the E_x is low enough so that gamma decay is the only channel
- The "leftovers" of higher generation γ-rays are excluded. [8]

The figure 3b and c shows some contamination from other isotopes, and these limits were used to avoid them in the spectra.

Values used in `rhosigchi.f`	
E_x upper lim.	4800 eV
E_x lower lim.	3000 eV
E_γ lower lim.	1000 eV

Table 1. The values used when runing the `rhosigchi.f` program.

The next step was to normalize the functions $\mathscr{T}(E_\gamma)$ and $\rho(E-E_\gamma)$ which were obtained obtained from the `rhosigchi.f` program. A program called `robin` was used to calculate the level density and spin-cutoff parameter. The spin-cutoff parameters calculated from `robin`, $\sigma_n = 7.378$ and $\sigma_p = 8.209$, were used in the program `D2rho`. In `D2rho` the level spacing was used, which were obtained from the RIPL-3 Handbook [12], to find the level density $\rho(S_n)$. The program `counting` normalized the experimental NLD to the known NLD at low energies (see figure 4). All crucial values used in `rhosigchi`, `robin`, `D2rho` and `counting` are shown in table 2.

root was then used to display the output from counting which are displayed in figure 1 and 2.

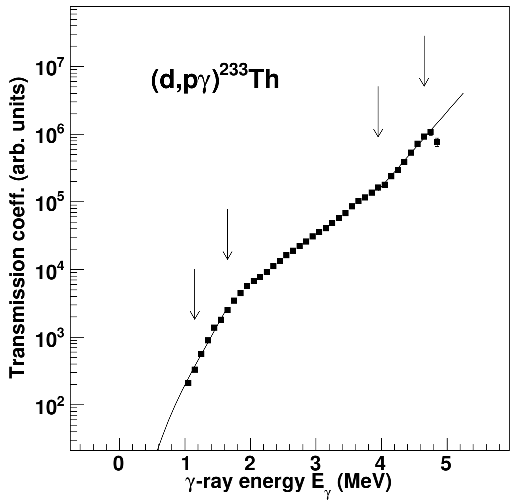

Figure 1. The transmission coefficient versus γ-ray energy. The arrows indicate the the ranges of experimental values used to fit the curve.

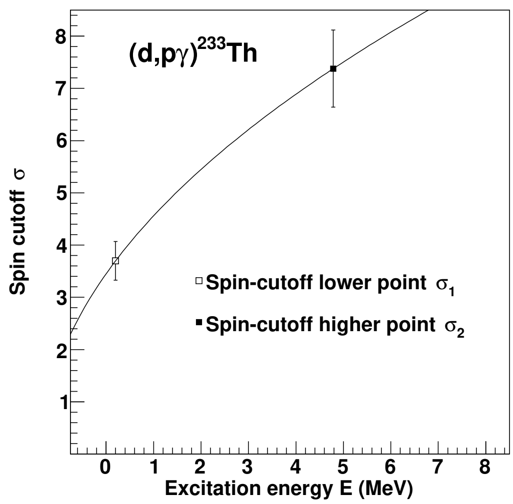

Figure 2. The two spin cutoff parameters, with estimated uncertainties of 10%.

The plots displayed with `root` were used in the final step where the normalization of $\mathscr{T}$ in figure 1 was done. The black line was fitted to the experimental values represented by the dotted lines by changing the positions of the displayed arrows. The normalized $\mathscr{T}$ was then used to calculate the γSF by equation 4.

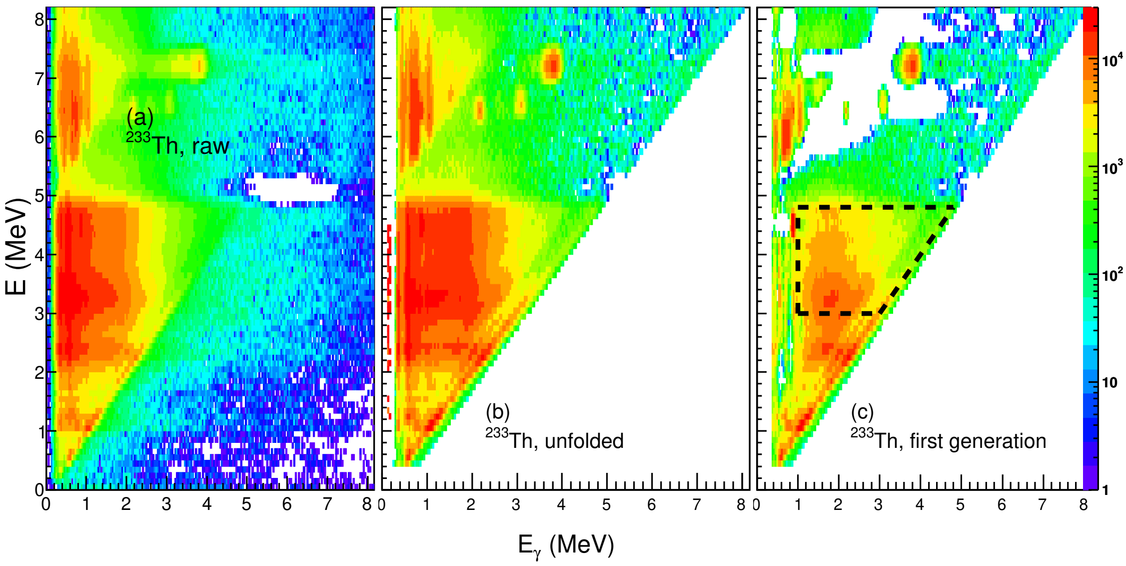

Figure 3. Initial excitation energy E versus γ-ray energy E_γ from particle-γ coincidences from the ^{232}Th(d, pγ)^{233}Th reaction. a) shows the raw spectrum, b) shows the unfolded spectrum and c) shows the first-generation γ-ray spectrum, with a stippled section to illustrate the part of the spectrum used for further analysis.

S_n[keV]	a [MeV^{-1}]	E_1[MeV]	$\sigma(S_n)$	D_0[eV]	$\rho(S_n)$[10^6MeV^{-1}]
4786.39(9)	25.909	-0.458	7.378±10%	16.5±0.4	6.659±1.329

Table 2. The parameters used to extract level densities for ^{233}Th at S_n. The value used for S_n was taken from ENSDF[10]. The level density parameter a, and total backshift parameter E_1 were both taken from E&B2009[11] and the neutron resonance spacings D_0 was found in the RIPL-3 Handbook[12]. The remaining parameters $\sigma(S_n)$ and $\rho(S_n)$ were found using the Oslo method.

IV Results

Through the data analysis both the NLD and γSF were found experimentally for ^{233}Th. The nuclear level density is shown in Figure 4, and the γ strength function in Figure 5.

In the low excitation energy region the level density has been normalized to the known discrete levels, i.e. the black line in Fig. 4. At high excitation energy the level density has been normalized to the level density extracted from the known neutron resonance spacing D_0 at the neutron separation energy S_n. D_0 was found from RIPL-3[12].
The level density shows a constant-temperature behavior, and the data is normalized to a constant-temperature level density with T_{CR} = 0.39 Mev.

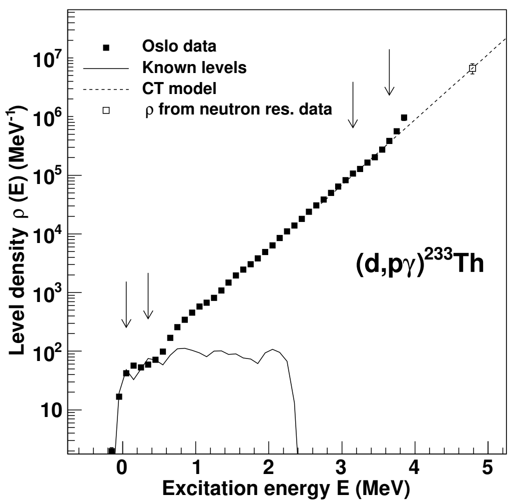

Figure 4. Level density for ^{233}Th. At low excitation energy E the experimental data is normalized to known discrete levels, and at high energy normalized to the level density extracted from known neutron resonance spacings D_0 at the neutron separation energy S_n

The γSF is calculated after normalizing the γ-ray transmission coefficient, $\mathscr{T}$, by Eq. 4. Then the resulting figure is found, as seen in Fig. 5

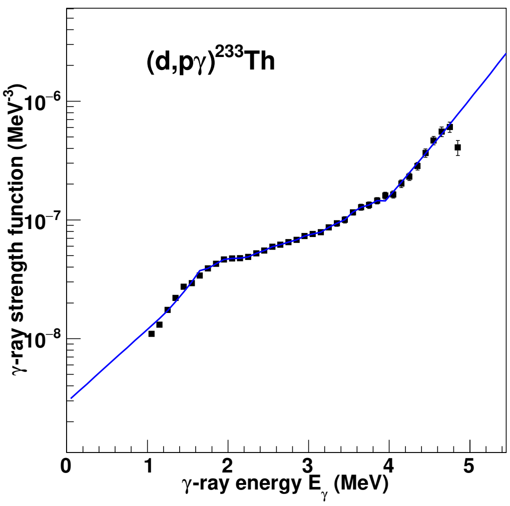

Figure 5. The γ-ray strength function for ^{233}Th.

V Discussion

The level density found in Fig. 4 is normalized to different values at low and high excitation energies. The resulting trend follows a constant-temperature behavior, except maybe for the final data-point at the highest excitation energy, which seems to deviate somewhat from the constant-temperature stippled line in Fig. 4. Published results with level density of this reaction also seem to be very similar, but a more thorough comparison could be done in the future.

As seen in Fig. 5 there appears to be a resonance in the region just below 2 MeV E_γ. This has been recognized in the literature as a scissors resonance [1, 3]. The scissors resonance is a resonance that can be naively described as the proton and neutron clouds oscillating against each other like scissor blades [13]. This enhancement is predicted [14] as $M1$ transitions in deformed nuclei.

VI Conclusion

The level density and γSF of ^{233}Th has been determined using the Oslo method. A constant-temperature behavior is seen in the level density, which has been reported in recent publications [2, 3].

An excess in the γSF is spotted in the region just below $E_\gamma = 2$MeV. This is interpreted as the quasicontinuum scissors resonance.

Further studies of these phenomena in the actinides could have large impacts on both reactor physics and astrophysics. The reaction rate predictions that can be calculated from these results could help understand both the nucleosynthesis in extreme environments in the universe, as well as providing better models for the complicated processes happening in nuclear reactors.

References

[1] Guttormsen, M. et al. Observation of Large Scissors Resonance Strength in Actinides. Phys. Rev. Lett. 109, 162503, DOI: 10.1103/PhysRevLett.109.162503 (2012).

[2] Guttormsen, M. et al. Constant-temperature level densities in the quasicontinuum of Th and U isotopes. Phys. Rev. C 88, 024307, DOI: 10.1103/PhysRevC.88.024307 (2013).

[3] Guttormsen, M. et al. Scissors resonance in the quasicontinuum of Th, Pa, and U isotopes. Phys. Rev. C 89, 014302, DOI: 10.1103/PhysRevC.89.014302 (2014).

[4] E. Fermi, *Nuclear Physics*, University of Chicago Press, Chicago (1950).

[5] M. Guttormsen, et al. *The First Generation of γ-Rays from Hot Nuclei.* Nuclear Inst. and Methods in Physics Research, A, vol. 255, no. 3, 1987, pp. 518–523.

[6] Guttormsen, Magne. *The Unfolding of Continuum -Ray Spectra.* Vol. 96-02, University of Oslo, Department of Physics, 1996.

[7] Schiller, A, et al. "Extraction of Level Density and Strength Function from Primary Spectra." *Nuclear Inst. and Methods in Physics Research, A*, vol. 447, no. 3, 2000, pp. 498–511.

[8] A. C. Larsen, Lecture FYS4515: *Extracting level density and γ-ray transmission coefficient from the first-generation matrix*, 17.10.2019

[9] D. M. Brink, Ph.D. thesis, Oxford University, 1955.

[10] Data extracted using the NNDC On-Line Data Service from the ENSDF database at www.nndc.bnl.gov/ensdf.

[11] T. Egidy and D. Bucurescu, *Experimental energy-dependent nuclear spin distributions*, Phys. Rev. C 80, 054310 (2009).

[12] RIPL-3 Handbook for calculation of nuclear reaction (2009); available at www-nds.iaea.org/RIPL-3/.

[13] N. Lo Iudice and F. Palumbo, *New isovector collective modes in deformed nuclei*, Phys. Rev. Lett. 41, 1532 (1978)

[14] Y. S. Chen and G. A. Leander, *Quasicontinuum properties of M1 spectra in the particle-rotor model*, Phys. Rev. C 26, 2607 (1982).