Progress on the Experimental test of the generalized Brink-Axel Hypothesis in ^{139}La nucleus

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Abstract. The Brink-Axel (BA) hypothesis is a foundational assumption in nuclear structure and astrophysics, postulating that the γ-ray strength function (GSF) for photo-absorption depends solely on the γ-ray energy and is independent of the excitation energy of the nucleus. However, experimental studies across various mass regions have produced conflicting results regarding its validity. In this work, we test the Brink-Axel hypothesis in the ^{139}La nucleus using particle-γ coincidence data from the ^{139}La(^{3}He,^{3}He'γ)^{139}La reaction measured at the Oslo Cyclotron Laboratory. Primary γ-ray spectra were extracted for a range of excitation energies below the neutron separation energy. In particular, the γ-ray strength functions (γSFs) were studied as a function of initial excitation energy over the γ-ray energy interval $1.5 \leq E_\gamma \leq 8.5$ MeV. The extracted GSFs show consistent slope and magnitude across all initial excitation energy bins, indicating no dependence on the populated nuclear states. These results provide experimental support for the Brink–Axel hypothesis in ^{139}La and contribute to the broader effort to determine the conditions under which the GSF exhibits excitation-energy dependence.

1 Introduction

The γ-ray strength function (GSF) characterizes the average probability of a nucleus undergoing γ decay or photoabsorption, expressed as a function of the γ-ray energy. It is very useful in the quasi-continuum region, where the density of quantum states is very high and their wave functions are very close to each other and impossible to resolve experimentally. The *downward* (γ decay) γ-ray strength $f(E_\gamma)\downarrow$ is related to the average partial γ decay width $\overline{\Gamma}$ and the nuclear level density $\rho(E_i, J^\pi)$ at the initial excitation energy E_i according to

$$f(E_\gamma)\downarrow = \frac{\overline{\Gamma}(E_i, E_\gamma)\,\rho(E_i, J^\pi)}{E_\gamma^{2\lambda+1}}, \tag{1}$$

where λ denotes the multipolarity of the transition. Conversely, the upward (γ absorption) strength $f(E_\gamma)\uparrow$ is linked to the photoabsorption cross section $\langle\sigma(E_\gamma)\rangle$ via

$$f(E_\gamma)\uparrow = \frac{\langle\sigma(E_\gamma)\rangle}{3(\pi\hbar c)^2 E_\gamma}, \tag{2}$$

where the quantities $\hbar$ and c are the reduced Planck's constant and the speed of light, respectively. The $f(E_\gamma)\downarrow$ and $f(E_\gamma)\uparrow$ are identical according to the principle of detailed balance, given that the same states are populated.

Furthermore, the generalized Brink-Axel (gBA) hypothesis, which is a modified version of the original Brink hypothesis, suggests that the *upward* and *downward* strengths do not depend on the properties of the initial and final states of a nucleus, such as excitation energy, spins and parities, but on the energy of a γ ray that the nucleus emits or absorbs [1, 2]. The gBA is very critical in nuclear physics and nuclear astrophysics because some experimental methods, such as the Oslo method [3] and ratio method [4], used to measure GSF are based on the assumption that the gBA is true across the nuclear chart. However, various studies have reported controversial results on the validity of the gBA. For instance, the work of Refs. [5, 6, 7] contradicted the generalized Brink-Axel hypothesis, while the results of Refs. [8, 9, 10] agree with the gBA hypothesis. Thus, the gBA is still questionable and needs to be thoroughly tested across the nuclear chart, as stated by Ref. [8].

In this paper, we report on the first experimental test of the validity of the generalized Brink–Axel hypothesis in ^{139}La nucleus. In particular, we investigated the dependence of the $downward$ γ-ray strength function on the initial excitation energy E_i.

2 Experimental methods

This work utilizes experimental data acquired at the Oslo Cyclotron Laboratory, as documented in Refs. [11], originally collected by researchers from iThemba LABS and the Oslo group for a different research purpose. A self-supporting, natural ^{139}La target with a thickness of 2.5 mg/cm^2 was bombarded with a 38 MeV ^{3}He beam to populate excited states in ^{139}La via the inelastic scattering reaction ^{139}La(^{3}He, ^{3}He$'$)^{139}La. Charged particles were detected using the SiRi array [12], which consists of 64 ΔE–E silicon detector telescopes, with thicknesses of 130 μm and 1550 μm for the front and back detectors, respectively. The array was positioned 50 mm from the target at a laboratory angle of $\theta_{\rm lab} = 47^\circ$ with respect to the beam axis, covering a total solid angle of approximately 6%. Coincident γ rays were recorded using the CACTUS array [13], consisting of 26 collimated $5'' \times 5''$ NaI(Tl) detectors arranged spherically around the target position. The total γ-ray detection efficiency of the array was 14.1% at $E_\gamma = 1.3$ MeV.

Particle–γ coincidence events were recorded within a 3 μs acquisition window, and a refined offline time gate of 50 ns was applied during analysis to suppress random coincidences for ^{139}La data. The measured ^{3}He energies were converted to excitation energies E_i of the residual ^{139}La nucleus using kinematics and Q-value of the reaction. Figure 1 depicts the first-generation matrix of ^{139}La obtained from the measured particle-γ coincidence events using the first generation method of Ref. [14]. This matrix displays the intensity of primary γ rays as a function of excitation energy E_x and E_γ.

The first generation matrix comprises first generation γ spectra $g(E_i, E_\gamma)$ which results from primary γ rays emitted at initial excitation energy E_i. These are normalized such that the likelihood of the nucleus to emit a γ ray of energy E_γ is given by

$$P(E_i, E_\gamma) = \frac{g(E_i, E_\gamma)}{\sum_{E_\gamma} g(E_i, E_\gamma)}, \tag{3}$$

In this work, we focus on studying the dependence of GSF on the initial excitation energy using the formalism derived by Ref. [8]. In particular, we began by extracting the γ-ray transmission coefficient $\mathcal{T}(E_i, E_\gamma)$, from the first generation matrix shown in figure 1, as a function of initial excitation energy and γ ray energy using the equation

$$\mathcal{T}(E_i, E_\gamma) = \frac{N(E_i)P(E_i, E_\gamma)}{\rho(E_i - E_\gamma)}, \tag{4}$$

where $\rho(E_i - E_\gamma)$ is the nuclear level density of initial excitation energy obtained using the Oslo Method, while $N(E_i)$ is a normalization parameter given by

$$N(E_i) = \frac{\int_0^{E_i} \mathcal{T}(E_\gamma)\rho(E_i - E_\gamma)\, dE_\gamma}{\int_0^{E_i} P(E_\gamma, E_i)\, dE_\gamma}. \tag{5}$$

Thus, the dependence of GSF on the initial excitation energy is obtained using

$$f(E_\gamma) = \frac{\mathcal{T}(E_\gamma)}{2\pi E_\gamma^3}. \tag{6}$$

This method allowed for the extraction of GSF at narrow initial excitation energy bins of 105 keV width. Thus, allowing a detailed investigation of the dependence of GSF ^{139}La on initial excitation energy.

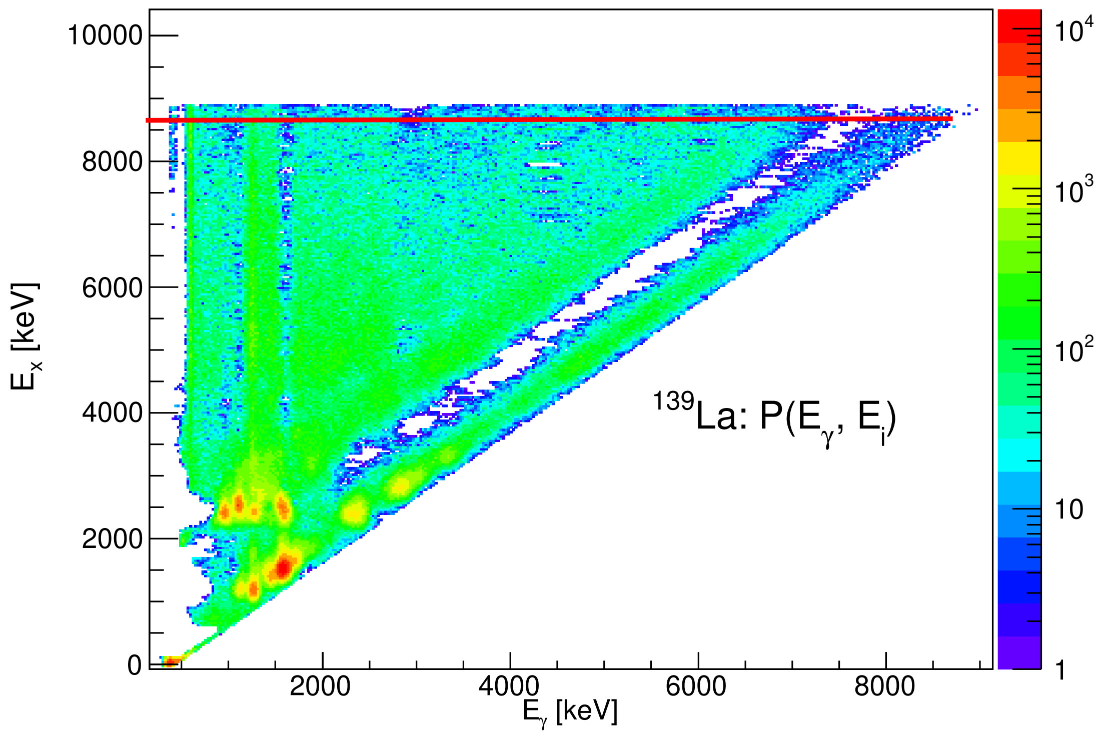

Figure 1: Primary γ-ray matrix of ^{139}La, showing γ-ray energy (E_γ) as a function of excitation energy (E_x).Primary matrix of .The horizontal red line marks the neutron separation energy (Sn) of the nucleus.

3 Results and Discussion

The experimental results on the dependence of the γ-ray strength function (γSF) of ^{139}La on the initial excitation energy E_i, as obtained through the high-resolution analysis of the primary γ-ray matrix are presented. The γSFs were extracted following Eqs. (3)–(5), starting from the normalized first-generation probability matrix $P(E_\gamma, E_i)$, which was constructed from the unfolded primary γ-ray matrix $g(E_i, E_\gamma)$ shown in Fig. 1.

Figure 2 shows the γSFs extracted for six initial excitation energy bins: (a) 3.85 MeV, (b) 4.12 MeV, (c) 4.40 MeV, (d) 4.67 MeV, (e) 4.94 MeV, and (f) 5.22 MeV. The experimental data points (black) are compared to the standard Oslo Method result (blue curve), representing an average strength function of ^{139}La over a wide excitation range. The standard Oslo Method data drops sharply to zero around to zero around $E_\gamma \approx 1.8$ MeV and $E_\gamma \approx 8.4$ MeV, as these represent the minimum and maximum of γ-ray energies where the standard Oslo Method was applied. Across all E_i bins, the shape and magnitude of the γSFs agree closely with the standard result. This agreement implies that the γ strength function is independent of the initial excitation energy. This finding supports the generalized Brink–Axel (gBA) hypothesis, which posits that the dipole γ-strength function depends solely on E_γ and not on the specific nuclear configurations involved.

The results for ^{139}La are in line with previous findings for ^{138}La [10], reinforcing the validity of the gBA hypothesis in the $A \approx 138 - 139$ region. They also confirm the reliability of the Oslo Method for investigating statistical γ decay in odd-mass rare-earth nuclei.

Conclusion

This study offers strong experimental evidence in support of the Brink–Axel hypothesis, which asserts that the γ-ray strength function depends solely on the γ-ray energy and not on the properties of the nuclear states involved. Using particle–γ coincidence data from the ^{139}La(^{3}He,^{3}He'γ)^{139}La reaction measured at the Oslo Cyclotron Laboratory, we extracted primary γ-ray spectra over a range of excitation energies below the neutron separation energy.

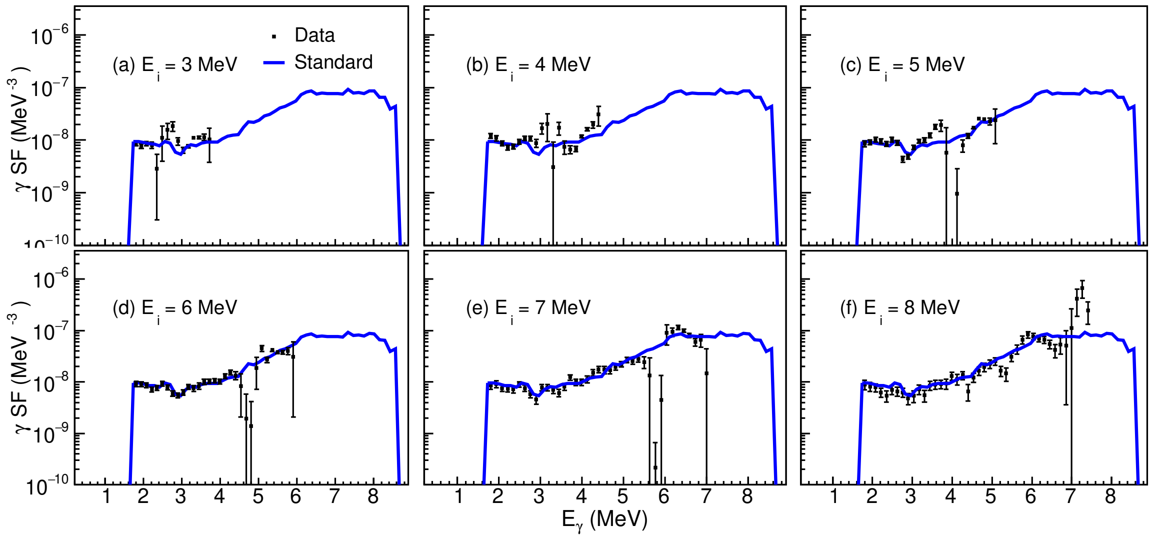

Figure 2: The γ-ray strength function of ^{139}La at different initial excitation energies.

The γSFs were evaluated as a function of initial excitation energy within the interval $1.5 \leq E_\gamma \leq 8.5$ MeV. The extracted γSFs exhibit consistent slope and magnitude across all excitation energy bins, showing no dependence on the populated nuclear states. These findings provide experimental support in confirming the Brink Axel hypothesis in ^{139}La and contribute to the broader effort to understand the conditions under which the γSF remains independent of excitation energy.

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