

## Scissors Mode of $^{162}\text{Dy}$ Studied from Resonance Neutron Capture

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**Abstract.** Multi-step cascade  $\gamma$ -ray spectra from the neutron capture at isolated resonances of  $^{161}\text{Dy}$  nucleus were measured at the LANSCE/DANCE time-of-flight facility in Los Alamos National Laboratory. The objectives of this experiment were to confirm and possibly extend the spin assignment of *s*-wave neutron resonances and get new information on photon strength functions with emphasis on the role of the *M1* scissors mode vibration. The preliminary results show that the scissors mode plays a significant role in all transitions between accessible states of the studied nucleus. The photon strength functions describing well our data are compared to results from  $^3\text{He}$ -induced reactions,  $(n,\gamma)$  experiments on Gd isotopes, and  $(\gamma,\gamma')$  reactions.

## 1 Introduction

Since theoretical prediction in 70's [1], the *M1* vibrational scissors mode (SM) has been studied using different probes of nucleus. After its experimental discovery by inelastic electron scattering on  $^{156}\text{Gd}$  [2], the behavior of SM was thoroughly investigated by analyzing intensities of *ground state M1* transitions observed from nuclear resonance fluorescence (NRF) experiments [3].

For deformed even-even rare-earth nuclei the energy of the mode,  $E_{\text{SM}}$ , was found to be  $\approx 3$  MeV, almost independent of  $A$ . The summed SM reduced strength,  $\Sigma B(\text{SM}) \uparrow$ , exhibits dependence on the square of nuclear deformation  $\delta$  with maximum of  $\approx 3\mu_N^2$  for strongly deformed rare-earth nuclei [4].

The importance of SM for transitions between excited states became clear from radiative neutron capture experiments [5, 6] as well as  $^3\text{He}$ -induced photon production [7]. Unfortunately, the SM strength of even-even rare-earth nuclei from  $^3\text{He}$ -induced experiments [8–11] reaches  $\Sigma B(\text{SM}) \uparrow = 6 - 7\mu_N^2$ , which is in disagreement with mutually consistent results from NRF and neutron capture experiments on Gd isotopes [12–15].

Results on PSF from analysis of multistep cascade (MSC) spectra obtained from measurement of photons in radiative neutron capture on isolated  $^{161}\text{Dy}$  resonances should shed more light on the issue of discrepancy between different experiments as the same isotope was measured in  $^3\text{He}$ -induced photon production [8, 11].

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## 2 Experimental setup and data processing

### 2.1 Experimental spectra

The experiment was performed at the neutron source LANSCE [16]. The 800-MeV proton pulsed beam strikes a tungsten spallation target with a repetition rate of 20 Hz. The neutrons with energies from subthermal up to about 1 MeV are sent to flight path 14 at the Manuel Lujan Jr. Neutron Scattering Center where the DANCE detector array is installed at 20 meters from the spallation target. The DANCE array consists of 160  $\text{BaF}_2$  scintillation crystals surrounding a sample and covering a solid angle of  $\approx 3.5\pi$  [17, 18]. A  $^6\text{LiH}$  shell about 6-cm thick is placed between the sample and the  $\text{BaF}_2$  crystals to reduce the scattered neutron flux striking the crystals. The remaining background due to scattered neutrons that penetrate the  $^6\text{LiH}$  shell and interact with the  $\text{BaF}_2$  crystals can be subtracted, see Refs. [12, 13].

The  $^{161}\text{Dy}$  target was enriched to 95.7%. Only  $\gamma$  cascades, which deposit all their energy in the detector are selected for analysis. The events corresponding to 25 and 22 strong resonances of  $J^\pi = 2^+$  and  $3^+$ , isolated by the time-of-flight technique, were used to construct the MSC spectra for different observed multiplicities  $m$ , i.e. spectra of energies belonging to a single cascade which are deposited in  $m$  detector clusters. A detector cluster is defined by all contiguous detector crystals that have fired during an event, see Refs. [17–19]. Thanks to this selection of events the resulting MSC spectra are virtually free of background.

### 2.2 Simulation of $\gamma$ decay

MSC spectra are products of a complicated interplay between Photon Strength Functions (PSFs) and Nuclear

Level Density (NLD). In our approach the determination of these quantities is accomplished by a trial-and-error approach in which the experimental MSC spectra are compared with the outputs of simulations based on various model assumptions for PSFs and NLD.

The  $\gamma$  cascades following the resonance neutron capture are generated using the DICEBOX algorithm [20] in which the partial radiation width  $\Gamma_{i\gamma f}$  between an initial level  $i$  above a critical energy  $E_{\text{crit}} = 1.87$  MeV and final level  $f$  is calculated as

$$\Gamma_{i\gamma f} = \sum_{XL} \xi_{XL}^2 \frac{f^{(XL)} E_{\gamma}^{2L+1}}{\rho(E_i, J_i, \pi_i)}, \quad (1)$$

where  $\rho(E_i, J_i, \pi_i)$  is a NLD of the initial states,  $f^{(XL)}$  are the PSFs for transitions of type  $X$  and multipolarity  $L$ , and  $\xi_{XL}$  is a random number from a normal distribution with a zero mean and unit variance. It ensures that individual widths  $\Gamma_{i\gamma f}$  fluctuate according to the Porter-Thomas distribution (PTD) [21]. The sum in Eq. (1) goes over all allowed types and multipolarities of transitions – only  $E1, M1$  and  $E2$  were considered,  $E2$  not affecting results.

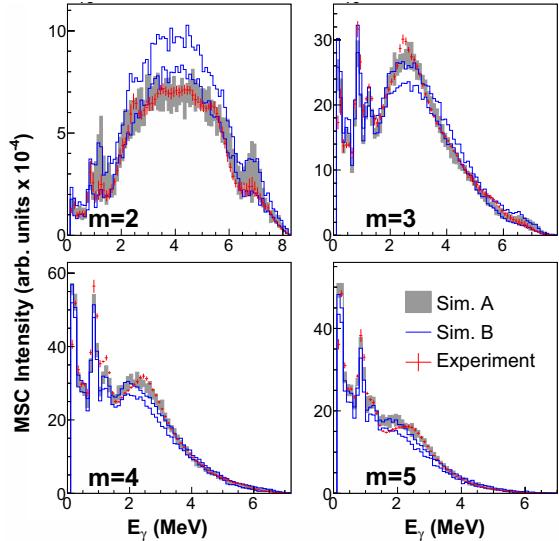
The simulated system of nuclear levels and intensities of transitions between them is called a nuclear realization (NR), for details see Ref. [20]. To get estimates of expected fluctuations of MSC spectra due to PTD fluctuations 20 independent NRs with given combination of PSFs and NLD were generated for each  $J^\pi$  of initial  $s$ -wave resonance, with  $10^5$  cascades in one NR.

The response of the DANCE detector to each generated cascade was simulated using the GEANT4 package that includes exact geometry of the detector system [19]. The resulting MSC spectra were compared with their experimental counterparts.

### 2.3 PSF and NLD models

The  $E1$  PSF for  $E_\gamma$  above neutron separation energy  $S_n$ , where these transitions dominate, seems to be consistent with the standard Lorentzian (SLO) model [22]. Many results for energies below  $S_n$  show that SLO is inadequate description of the  $E1$  PSF at these  $E_\gamma$ . For this reason other models have to be tested. In this contribution we restrict ourselves to the KMF [22] and the Modified Generalized Lorentzian (MGLO) [14] models.

The  $M1$  transitions play a crucial role in the decay of highly excited nuclear states in deformed nuclei. In addition to the above-mentioned SM two models were used for  $M1$  transitions. In the spin-flip (SF) model, the  $M1$  PSF has a Lorentzian shape with the energy of about 7 MeV and width of 2 – 4 MeV [22], while in the single-particle (SP) model, the  $M1$  PSF is a constant independent of  $E_\gamma$ . For these two  $M1$  models we assumed the strict validity of Brink hypothesis [23], which says that the PSF shape is independent of the excitation energy. We adjusted the absolute value of the  $M1$  PSF to obtain the ratio of  $\approx 7$  between  $E1$  and  $M1$  PSFs for  $E_\gamma \approx 7$  MeV, which seems to be well determined from average resonance capture [24].



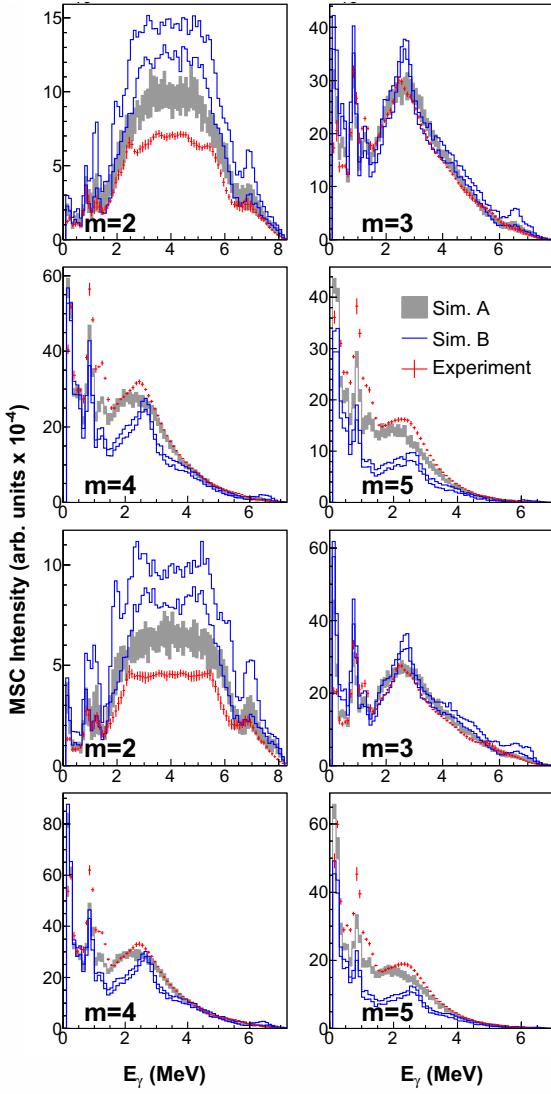
**Figure 1.** A comparison between experimental and simulated MSC spectra for  $2^+$  resonances. The MGLO model with  $k = 3$  was adopted for  $E1$  PSF. For  $M1$  PSF all 3 components – namely the SF, SP ( $5 \times 10^{-9} \text{ MeV}^{-3}$ ) and the SM ( $E_{\text{SM}} = 3$  MeV,  $\Sigma B(\text{SM}) \uparrow = 5.8 \mu_N^2$ ) components were assumed to follow the Brink hypothesis in simulation A, while in simulation B the SM component was considered only for states under 1 MeV. The corridor for simulated data corresponds to “one sigma” confidence interval obtained from simulation of 20 NRs.

Constant-Temperature (CT) and the Back-Shifted Fermi Gas (BSFG) models of NLD, given by closed-form formulas with the adjustable parameters taken from Refs. [25, 26], were used in simulations. Only basic tests were performed with CT model as the BSFG one led to the best reproduction of the Gd experimental MSC spectra, see Refs. [12–14], and is reasonably consistent with results from  ${}^3\text{He}$ -induced reactions in rare-earth nuclei. The spin dependence of the BSFG model had the standard form [26] and no parity dependence of NLD was assumed. The parametrization of NLD models was taken from [25].

## 3 Results

The SLO model seems to fail in describing the experimental MSC spectra no matter what combination of  $M1$  PSF and NLD models is used. The main reason is overestimation of intensities in  $m = 2$  MSC spectra. The KMF model suffers similarly to SLO model, being unable to reproduce simultaneously the intensities in the middle part of both  $m = 2$  MSC spectra and the marked maxima at  $\approx 2.5$  MeV in  $m = 3$  MSC spectra. A reasonable agreement was achieved using the MGLO model with the parameter  $k \approx 3$ , see Ref. [14] for explanation of the parameter value.

To reproduce the experimental MSC spectra the SM as well as SP and SF have to be introduced in  $M1$  PSF. The best agreement achieved so far, see Fig. 1, is obtained with  $E_{\text{SM}} = 3$  MeV, SM damping width of  $\approx 1.4$  MeV and the total summed strength  $\Sigma B(\text{SM}) \uparrow = 5.8 \mu_N^2$ . The SP



**Figure 2.** A comparison between experimental and simulated MSC spectra for both resonance spins. For simulation A the MGLO model with  $k = 3$  was adopted for  $E1$  PSF with  $M1$  PSF containing the SF and the SM component ( $E_{SM} = 3$  MeV,  $\Sigma B(SM) \uparrow = 2.67 \mu_N^2$ ), which are the PSFs reasonably describing MSC spectra in  $^{158}\text{Gd}$ , see [12–14]. The PSFs describing  $^3\text{He}$ -induced photon production data, see Ref. [11], were used for simulation B. The corridor for simulated data corresponds to “one sigma” confidence interval obtained from simulation of 20 NRs.

part of  $M1$  PSF with value of  $\approx 5 \times 10^{-9} \text{ MeV}^{-3}$  is necessary. It was found that the SM has to be build on all accessible levels, i.e. it follows the Brink hypothesis [23]. For the sake of clarity the extreme case, where the SM is built only on states with excitation energy smaller than 1 MeV, is shown in Fig. 1. The  $E1$  nature of the resonance structure near  $\approx 3$  MeV was ruled out from our analysis. It should be emphasized that the obtained parametrization of  $E1$  and  $M1$  PSFs, in combination with the BSFG model of NLD, leads to the reproduction of the experimental value of the total  $\gamma$  adiabatic width of  $s$ -wave neutron resonances [22].

The  $E1$  and  $M1$  PSFs coming from the study of the decay of isolated  $s$ -wave neutron resonances of even-even

Gd isotopes at DANCE [12–14] are not able to reproduce the measured MSC spectra. The same conclusion holds for the PSFs and NLD of  $^{162}\text{Dy}$  extracted from data measured in  $^3\text{He}$ -induced reactions [8, 11], see Fig. 2. The total observed strength of SM is roughly two times higher than the strength of the ground-state transitions observed in NRF experiments [3] and the strength from  $(n, \gamma)$  on Gd. It is comparable to results from  $^3\text{He}$ -induced reactions.

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