EPJ Web of Conferences **93**, 01036 (2015)
DOI: 10.1051/epjconf/ 20159301036

Photon Strength Functions from Two-Step γ Cascades Experiment on ^{155,157}Gd

J. Kroll[1,2,a], S. Valenta[2], M. Krtička[2], F. Bečvář[2], I. Tomandl[3] and G. E. Mitchell[1,4]

[1] North Carolina State University, Raleigh, NC-27695, USA
[2] Charles University in Prague, CZ-18000 Prague 8, Czech Republic
[3] Nuclear Physics Institute, Czech Academy of Science, CZ-25068 Řež, Czech Republic
[4] Triangle Universities Nuclear Laboratory, Durham, NC-27708, USA

Abstract. Spectra of two-step γ cascades following neutron capture in ^{155,157}Gd were measured using the two-HPGe-detector facility installed at a pure subthermal neutron beam of the LVR-15 reactor in Řež near Prague. The main objective of this experiment was to get new information on photon strength functions with the emphasis put on the role of $M1$ scissors mode vibration. An analysis of accumulated γ-ray spectra, made within the statistical model, leads to the conclusion that the scissors mode significantly affects γ decay of all states of studied nuclei. The obtained results for energy, damping width and summed $B(M1)\uparrow$ strength of the scissors mode are compared with what has been deduced from neutron capture experiments performed at DANCE detector installed in Los Alamos National Laboratory, NRF data for the ground state scissors mode and from the data on ^{3}He-induced reactions using the so-called Oslo method.

1 Introduction

In medium and heavy mass nuclei detailed information on the properties of nuclear levels and transitions between them usually exists only at very low excitation energies where the spacing of levels is high. Obtaining reliable spectroscopic information on levels at higher excitation energies becomes very difficult. It is believed that properties of the nucleus in this region can be described by the statistical model [1] in terms of the nuclear level density (NLD) and a set of photon strength functions (PSFs) for different types and multipolarities of transitions. These quantities are important for correct description of reaction rates in many different reactions and are especially needed in nuclear astrophysics and in the development of advanced nuclear reactors.

One of the most important features of the PSFs in well-deformed nuclei is the presence of the $M1$ vibrational scissors mode (SM) that has been experimentally confirmed in several different reactions. Unfortunately, results from these reactions, especially on the strength of the SM, are not fully consistent. The strength of the mode in even-even well-deformed nuclei from electron and photon scattering [2, 3], as well as from decay of isolated s-wave neutron resonances [4–6], seems to be reasonably consistent with the strength of $\Sigma B(\mathrm{SM})\uparrow = 2 - 3\ \mu_N^2$ while data from particle-induced γ decay measured at Oslo [7–10] indicate significantly higher strength of $\Sigma B(\mathrm{SM})\uparrow = 6 - 7\ \mu_N^2$. Any additional information which sheds light on the properties of the SM is thus appreciated.

[a] e-mail: jkroll@ncsu.edu

2 Experimental setup and data processing

2.1 Two-step cascade γ-ray spectra

The measurement of two-step γ cascades (TSCs) following thermal neutron capture on ^{155,157}Gd targets was performed at the 15 MW light-water research reactor at Řež.

A beam of thermal neutrons, collimated to a cross section of about 2.0×0.2 cm^2 at the sample position, had a flux of 3×10^6 n·cm^{-2}· s^{-1}. Neutron capture γ-rays in ^{156}Gd were detected by two HPGe detectors with efficiencies of 28% and 22% while in ^{158}Gd one 22% HPGe and one 15% Ge(Li) detector were used. The detectors were placed on the opposite sides of the target at 90° with respect to the beam. The distance between the cylindrical surface of each detector and the center of the sample was 24 mm. The samples enriched to 91.1% and 82.3% in the form of Gd oxides were used for ^{155}Gd and ^{157}Gd, respectively. Measurements lasted for about 300 hours for both isotopes. ADC signals representing deposited γ-ray energies in the detector pair, together with the detection time difference, were recorded in list mode for each neutron capture event and were processed off-line.

The spectra of γ-ray energy sums from coincident events following capture in ^{157}Gd are shown in Fig. 1. The peaks that are relevant for the present study originate from the deposition of all of the energy carried by two contiguous γ's following the condition that the first one initiates at the thermal neutron capturing state and the second one ends at a low-lying level of product nucleus. These peaks are labeled with the J^π value and the excitation energy of the corresponding low-lying (final TSC) level. Each of these "full energy" peaks (FEP) is accompa-

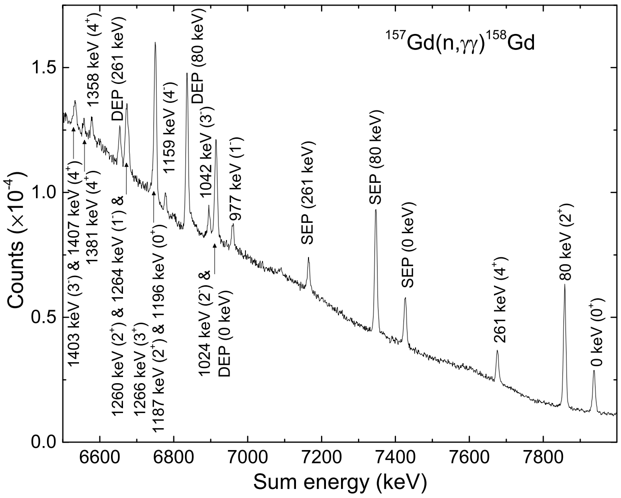

Figure 1. Spectra of γ-ray energy sums from capture in ^{157}Gd. See text for explanation of the labeling.

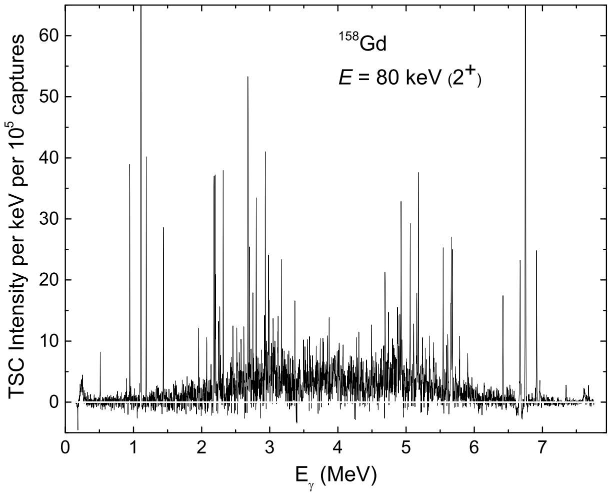

Figure 2. TSC spectrum for the first 80 keV (2^+) level in ^{158}Gd.

nied by its single-escape (SEP) and double-escape (DEP) satellite peaks.

Energies deposited in one of the detectors under the condition that the γ-ray energy sum from both detectors fell to the FEP corresponding to a TSC final level were used for construction of the background free TSC spectra ending at different levels, see Refs. [11, 12] for details of construction of TSC spectra. TSC spectra were further corrected for detector efficiency and vetoing effect coming from detection of a γ decaying the final TSC level. The spectra can be expressed in absolute intensities per neutron capture using known information on the intensity of a distinct TSC cascade via well-resolved low-lying level. The TSC transitions populating 89 keV (2^+) and 288 keV (4^+) levels through the 1248 keV (3^+) level in ^{156}Gd and 0 keV (0^+) and 80 keV (2^+) levels through the 1187 keV (2^+) level in ^{158}Gd with the intensities from Ref. [13] were used for this absolutization.

In total we constructed TSC spectra to 7 and 8 final levels in ^{156}Gd and ^{158}Gd, respectively. The TSC spectrum obtained for the first $J^\pi = 2^+$ state in ^{158}Gd is shown in Fig. 2.

2.2 Simulation of γ decay

TSC spectra are products of a complicated interplay between PSFs and NLD. To learn something about these quantities we adopted a trial-and-error approach in which we compare experimental TSC spectra with the outputs of simulations based on various model assumptions for PSFs and NLD.

The γ cascades following the thermal neutron capture are generated using the DICEBOX algorithm [1]. The algorithm takes into account Porter-Thomas fluctuations of partial radiation widths [14] which allows us to treat correctly uncertainties coming from simulations. These uncertainties were obtained from simulation of 10^5 decays in each of 50 “artificial” nuclei. To suppress fluctuations as well as experimental uncertainties we compare experimental and simulated TSC spectra binned into relatively coarse bins of the width of 100 keV.

Only transitions of $E1$, $M1$ and $E2$ types are considered in simulations. It is well known that for γ-ray energies above neutron separation energy S_n the $E1$ transitions play a dominant role. The $E1$ PSF at these energies seems to be consistent with the standard Lorentzian (SLO) model [15]. Since the shape of the $E1$ PSF below S_n is not well known, we tested also the KMF [15] and the Modified Generalized Lorentzian (MGLO) [6] models, which applicability for E_γ below S_n has been shown in Refs. [4–6].

The $M1$ transitions also play an important role in the decay of highly excited nuclear states. In addition to the SM, mentioned already in Sec. 1, two models were used for $M1$ transitions. In the spin-flip (SF) resonance model, the $M1$ PSF had a Lorentzian shape with the energy at about 7 MeV and width of $2 - 4$ MeV [15], while in the single-particle (SP) model, the $M1$ PSF is a constant independent of γ-ray energy. For these two $M1$ models we assumed the strict validity of Brink hypothesis [16], which says that the PSF shape is independent of the excitation energy. We usually adjusted the absolute value of the $M1$ PSF to obtain the ratio of $\approx$7 between $E1$ and $M1$ PSF for $E_\gamma \approx 7$ MeV, which seems to be well determined from average resonance capture experiments [17]. We found that $E2$ transitions do not affect the interpretation of our data.

The Back-Shifted Fermi Gas (BSFG) model of NLD, given by closed-form formula with the adjustable parameters taken from Refs. [18, 19], was used in our simulations. This model led to the best reproduction of the experimental MSC spectra, see Refs. [4–6], and is reasonably consistent with Oslo results in rare-earth nuclei. The spin dependence of the used BSFG model has the standard form [19] and no parity dependence was assumed.

3 Results

For both studied Gd nuclei we achieved a reasonable agreement between simulated and measured TSC spectra

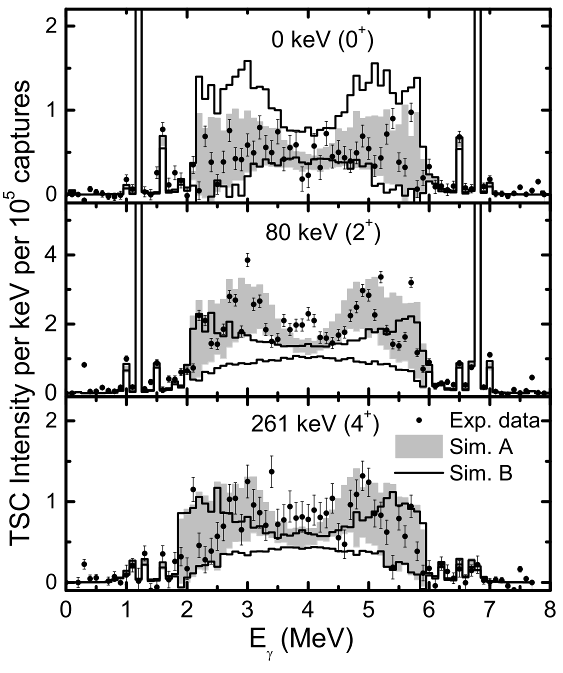

Figure 3. A comparison between experimental and simulated TSC spectra for three final TSC levels (indicated in Figure) of ^{158}Gd product. The MGLO model with $k = 3.0$ was adopted for $E1$ PSF. For $M1$ PSF both the SF and the SM ($E_{\rm SM} = 3$ MeV, $\Sigma B({\rm SM})\uparrow = 2.67\ \mu_{\rm N}^2$) components were assumed to follow the Brink hypothesis in simulation A, while in simulation B the SM component was considered only for the ground-state transitions. The corridor for simulated data corresponds to "one sigma" confidence interval obtained from simulation of 50 artificial nuclei.

with several $E1$ PSF models. Specifically, the allowed $E1$ models were the KMF model and the MGLO model with the parameter $k \approx 2-3$, see Ref. [6] for explanation of the parameter value.

We have never been able to reproduce experimental TSC spectra unless we postulate a resonance-like component of $M1$ PSF at ≈ 3 MeV which is in agreement with the Brink hypothesis [16], see Fig. 3. Postulating such a component in $E1$ PSF did not work. We interpret this finding as a manifestation of a resonance-like contribution of the SM to the $M1$ PSF. Within this interpretation the SM is responsible for the enhancement of transitions with $E_\gamma \approx 3$ MeV between all accessible nuclear levels.

Assuming the Lorentzian shape of the SM, the position of this mode was found to be $E_{\rm SM} = 2.8 - 3.0$ MeV and $2.9 - 3.2$ MeV and damping width $\Gamma_{\rm SM} = 0.8 - 1.5$ MeV and $0.6 - 1.5$ MeV for ^{156}Gd and ^{158}Gd products, respectively. Comparison of simulations with experiment allows us to determine only the "minimum" possible strength of the scissors mode. This minimum strength is $\Sigma B({\rm SM})\uparrow\approx 2.2\ \mu_{\rm N}^2$ and $1.8\ \mu_{\rm N}^2$ for ^{156}Gd and ^{158}Gd, respectively. Increase of the SM strength from this minimum value does not affect the quality of agreement between simulated and experimental TSC spectra. In case of ^{156}Gd product nucleus it was also necessary to add a non-resonant SP component of the $M1$ strength $0.5 - 3 \times 10^{-9}$ MeV^{-3} to reproduce experimental spectra. No additional SP component was needed for ^{158}Gd product but its presence cannot be ruled out.

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 radiation width of s-wave neutron resonances [15].

The results obtained for $E1$ PSF, as well as for the minimum possible strength of the SM, are in excellent agreement with the results coming from the study of the decay of isolated s-wave neutron resonances at DANCE [4–6]. They are also fully consistent with the strength of the ground-state transitions observed in NRF experiments [3]. Specifically, our minimum values of the $M1$ strength are slightly smaller than that observed in NRF experiments. Obtained values of the minimum SM strength are significantly lower than the total SM strength observed in ^{3}He-induced reactions on even-even Dy [9, 10], Er [7] and Yb [8] isotopes. Unfortunately, there are no Oslo data for Gd isotopes that would be directly comparable with our results.

Acknowledgements

This work was supported in part by the U. S. Department of Energy Grants No. DE-NA0001784 and No. DE-FG02-97-ER41042 and by the Grant No. 13-07117S of the Czech Science Foundation.

References

[1] F. Bečvář, Nucl. Instr. Meth. A **417**, 434 (1998)
[2] D. Bohle *et al.*, Phys. Lett. B **137**, 27 (1984)
[3] U. Kneissl *et al.*, Prog. Part. Nucl. Phys. **37**, 349 (1996)
[4] A. Chyzh *et al.*, Phys. Rev. C **84**, 014306 (2011)
[5] B. Baramsai et al., Phys. Rev. C **87**, 044609 (2013)
[6] J. Kroll et al., Phys. Rev. C **88**, 034317 (2013)
[7] E. Melby *et al.*, Phys. Rev. C **63**, 044309 (2001)
[8] A. Voinov *et al.*, Phys. Rev. C **63**, 044313 (2001)
[9] M. Guttormsen *et al.*, Phys. Rev. C **68**, 064306 (2003)
[10] H. T. Nyhus *et al.*, Phys. Rev. C **81**, 024325 (2010)
[11] J. Honzátko *et al.*, Nucl. Instr. Meth. A **376**, 434 (1996)
[12] M. Krtička *et al.*, Phys. Rev. C **77**, 054319 (2008)
[13] R. B. Firestone, private communication
[14] C. E. Porter *et al.*, Phys. Rev. **104**, 483 (1956)
[15] R. Capote *et al.*, Nucl. Data Sheets **110**, 3107 (2009)
[16] D. M. Brink, Ph.D. thesis, Oxford University, 1955
[17] L. M. Bollinger *et al.*, Phys. Rev. C **2**, 1951 (1970)
[18] T. von Egidy *et al*, Phys. Rev. C **72**, 044311 (2005)
[19] T. von Egidy *et al*, Phys. Rev. C **80**, 054310 (2009)