Journal of Physics: Conference Series **533** (2014) 012008 doi:10.1088/1742-6596/533/1/012008

News on the Scissors Mode

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Abstract. We report on our recent nuclear resonance fluorescence experiments on ^{152,154,156}Gd. Decay branches of the scissors mode to intrinsic excitations are observed. They are interpreted as a new signature for a spherical-to-deformed nuclear shape phase transition.

1. Introduction

Atomic nuclei provide examples of strongly interacting two-component fermionic quantum systems. The nuclear proton-neutron degree of freedom and its fundamental impact on the formation of nuclear structures, e.g. [1] represent one of the central aspects of modern nuclear structure physics. The structure of collective nuclear excitations is determined by the nuclear shell structure that itself evolves as a function of proton and neutron numbers, e.g., [2]. Nuclear excited states that partly involve an out-phase coupling of valence protons and valence neutrons such as the class of mixed-symmetry states of vibrational nuclei [3, 4] or the scissors mode of deformed nuclei [5, 6] are particular sensitive to the details of the effective proton-neutron interaction in the nuclear valence shell.

The evolution of nuclear shells and the residual interaction between valence protons and neutrons dominate the formation of nuclear deformation and collectivity. Depending on particle number a rather sudden onset of nuclear deformation can occur at so-called shape phase transitional points in the nuclear landscape. Near the shape phase transitions the fluctuations of nuclear deformation are large and shape excitations occur at rather low excitation energies. Examples of such sudden shape changes as a function of nucleon number are the stable $N = 90$ isotones [7]. At these points the filling of nuclear orbitals and their relative single-particle energies due to the residual proton-neutron interactions are such that collective nuclear quantum states can form within the valence shell with wave functions that include many basis states with proton excitations and neutron excitations that coherently couple in phase.

Recently, experimental evidence has been provided that this in-phase coupling of proton and neutron valence-shell excitations simultaneously leads to the occurrence of nuclear valence-shell excitations with partial out-of-phase coupling of valence protons and neutrons [1]. This

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represents a closely related aspect of the nuclear proton-neutron degree of freedom. Indeed, nuclear excitations may be classified according to the proton-neutron symmetry of their wave functions, either in terms of isospin in the framework of models that use fermionic nucleons as the fundamental degree of freedom or in terms of F-spin [8] in approximate bosonic nuclear models [9]. While, except for $N = Z$ nuclei, excited nuclear states at low energy (*e.g.*, at considerably lower energy as compared to the particle separation threshold) all have isospin quantum number $T = T_< = |N - Z|/2$, there occur states at rather low excitation energies with F-spin quantum numbers that differ from the F-spin of the ground state $F_{\rm gs} = F_{\rm max} = (N_\pi + N_\nu)/2$. Here $N_{\pi(\nu)}$ is half the number of valence protons (neutrons) or corresponding valence holes. Nuclear excitations with F-spin quantum number $F < F_{\rm max}$ have previously been called [10] mixed-symmetry states (MSSs) within the framework of the interacting boson model (IBM). Prominent examples of MSSs are the $J^\pi = 1^+$ scissors mode [5, 6, 9, 11, 12, 13, 14] in deformed nuclei or the mixed-symmetry $2^+_{1,\rm ms}$ one-phonon vibration for spherical nuclei [3, 4, 10]. Information on the proton-neutron symmetry of the low-lying nuclear states, including the ground state, its collective excitations, and MSSs, in nuclei that are as close as possible to the shape phase transitional point is desirable for a detailed understanding of the role of the nuclear proton-neutron degree of freedom in the formation of collective nuclear structure. Such information is indispensable when nuclei are used as quantum laboratories for fundamental interactions, such as searches for neutrinoless double-beta ($0\nu\beta\beta$) decay or searches for signals from scattering reactions between nuclei and Weakly Interacting Massive Particles (WIMPs) that are expected as candidates for the Dark Matter in the universe.

We have recently demonstrated [15] that information on the decay pattern of the scissors mode can provide sensitive constrains for nuclear models used for estimating the nuclear matrix elements (NMEs) for $0\nu\beta\beta$-decay rates. For instance, the IBM is used to calculate nuclear matrix elements for neutrinoless double β ($0\nu\beta\beta$) decays [16]. Especially for the double-β emitters ^{154}Sm and ^{150}Nd, sensitive information on the proton-neutron symmetry of the low-energy eigenstates is needed for a reliable calculation of $0\nu\beta\beta$ matrix elements within the IBM. Details on the decay pattern of the scissors mode of ^{154}Gd had a significant impact on the estimates for the branching ratio of the $0\nu\beta\beta$ decay of ^{154}Sm to ^{154}Gd [15].

2. Experiments

Photon-scattering experiments were performed exploiting the Darmstadt High Intensity Photon Setup (DHIPS) [17] at the Superconducting DArmstadt electron LINear ACcelerator (S-DALINAC) and the High Intensity $\vec{\gamma}$-ray Source (HI$\vec{\gamma}$S) [18] at the Triangle Universities Nuclear Laboratories (TUNL).

At DHIPS bremsstrahlung-photon beams are produced by stopping the electron beam in a radiator. The resulting bremsstrahlung-photon beams were scattered off the targets of interest. The scattered photons were detected by two or three large-volume high-purity germanium detectors (HPGe) positioned at polar angles 90° and 130° with respect to the incident γ-ray beam. The resonant photon-scattering cross sections $I_{s,f} = g\pi^2(\hbar c/E_\gamma)^2\Gamma_0\Gamma_f/\Gamma$ were measured relative to the calibration lines stemming from ^{27}Al [19]. Here, $g = (2J + 1)/(2J_0 + 1)$ is a statistical factor. The total level width $\Gamma = \hbar/\tau$ and the partial decay width to the ground (final) state Γ_0 (Γ_f) are only accessible if all decay intensity ratios Γ_f/Γ are determined. The partial decay widths $\Gamma_{f,\pi\lambda}$ are propertional to the reduced transition strengths $B(\pi\lambda; J^\pi \to J^\pi_f)$.

For the investigation of ^{152}Gd a target consisting of 2,525 mg Gd_2O_3 powder enriched to 32.5% in the isotope ^{152}Gd and 440 mg Al was used. Besides the transitions stemming from other stable Gd isotopes, the γ decays of dipole excited states of ^{152}Gd to the ground state, to the first excited 2^+ state, and for the state at 3.14 MeV also to the first excited 0^+ state could be observed. For the investigation of ^{154}Gd details about setup and data analysis can be found in Ref. [15].

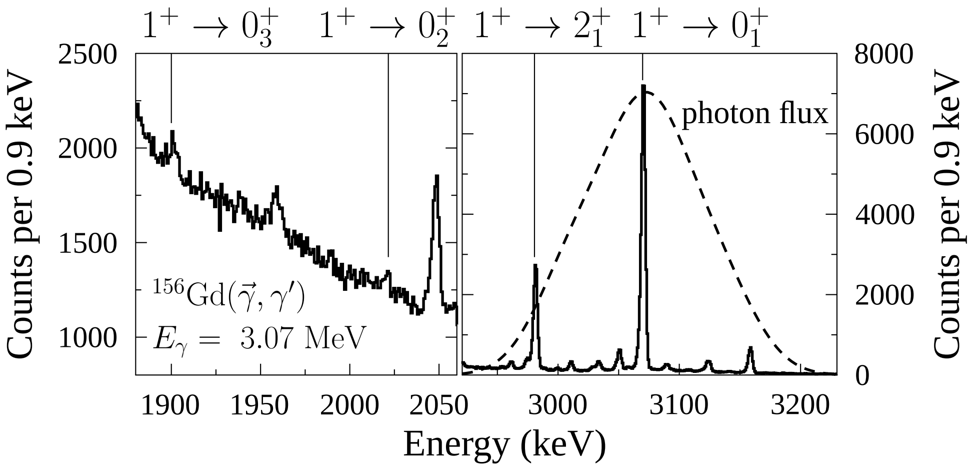

Figure 1. ^{156}Gd$(\vec{\gamma},\gamma')$ spectrum taken at $\theta = 135°$, $\phi = 0°$ at HI$\vec{\gamma}$S. Deexciting transitions from the $J^\pi = 1^+$ scissors mode state at 3.07 MeV to the 0^+_1, 2^+_1, 0^+_2, and 0^+_3 states could be observed. The dashed curve shows schematically the photon-flux distribution.

HI$\vec{\gamma}$S provides quasi-monoenergetic linearly-polarized γ-ray beams with tunable energies well suited for NRF measurements [20]. The γ rays are produced in Compton-backscattering of internal FEL-photons on electrons. After collimation the spectral distribution is about 3% of the mean γ-ray energy. The γ-beam was scattered off a Gd_2O_3 target enriched in the isotope ^{156}Gd to 93.79% with a total weight of 11.62 g. The quasi-monochromatic beam was used to excite $J^\pi = 1^+$ states around 3.07 MeV in ^{156}Gd. Their γ decays were studied with four HPGe detectors under polar angles of 135° and azimuthal angles of 0°, 90°, 180°, and 270°. Figure 1 shows the $(\vec{\gamma},\gamma')$ spectrum. The γ decay lines of the 1^+ scissors mode at 3.07 MeV to the ground state, to the first excited 2^+ state, to the 0^+_2 state, and to the 0^+_3 state are clearly visible at 3069, 2980, 2020, and 1900 keV. From the peak areas the intensity ratios Γ_f/Γ were deduced.

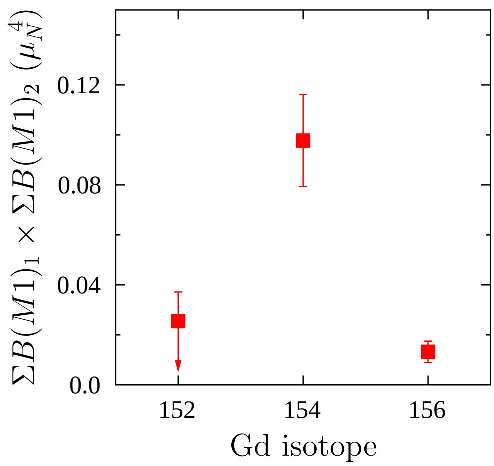

Figure 2. Product of the $M1$ transition strengths of scissors mode states to the 0^+_2 state and to the 0^+_1 ground state for ^{152,154,156}Gd. At ^{154}Gd the $M1$ product shows a distinct maximum.

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3. Results

Total $B(M1)$ excitation strengths of $J = 1$ states in the energy region of the scissors mode was measured for ^{152,154}Gd. These yield $\sum B(M1) \uparrow = 0.45(9)\ \mu_N^2$ for 152Gd and $3.12(36)\ \mu_N^2$ for 154Gd. $M1$ branching ratios of those states to the first excited 0^+ state were observed in all three isotopes: ^{152,154,156}Gd. The total $M1$ transition strengths for these $1^+_{sc} \rightarrow 0^+_2$ transitions were deduced to $\sum B(M1; 1^+_{sc} \rightarrow 0^+_2) = 0.17(7)$, $0.094(14)$, and $0.013(4)\ \mu_N^2$ for ^{152,154,156}Gd, respectively.

The $M1$ product of the transitions strengths to the 0^+_2 state and to the ground state

$$B(M1)_1 \times B(M1)_2 \equiv B(M1; 1^+_{sc} \rightarrow 0^+_1) \times B(M1; 1^+_{sc} \rightarrow 0^+_2) \tag{1}$$

is given in Fig. 2. The product exhibits a pronounced maximum at the $N = 90$ isotope ^{154}Gd and, thus, can be considered as a new signature for a shape phase transition. Work along these lines are in progress.

4. Conclusion

With the combination of different photon scattering experiments a novel decay branch (and its branching ratio) of $J^\pi = 1^+$ scissors mode states of ^{152,154,156}Gd to their first excited 0^+ state were observed. In addition, for the first time absolute excitation strengths of the scissors mode of ^{152,154}Gd were measured in photon scattering experiments. The $B(M1)_1 \times B(M1_2$ product exhibits a distinct maximum at the $N = 90$ shape phase transitional point. This quantity may represent a new signature for a spherical-to-deformed nuclear shape phase transition.

5. Acknowledgments

The authors thank the S-DALINAC accelerator crew and the TUNL staff for delivering excellent beams. This work was supported by the Deutsche Forschungsgemeinschaft under grant No. SFB 634 and No. ZI 510/4-2 and partly by the Alliance Programme of the Helmholtz Association (HA216/EMMI), BMBF-Verbundforschungsprojekt No. 06DA7047I, Fondecyt No. 1120462, and U.S. DOE Grant No. DE-FG-02-91ER-40608. N.P. thanks the Bulgarian Science Foundation and the DAAD for support.

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