Probing the $E2$ properties of the scissors mode with real photons

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Abstract. The $E2/M1$ multipole mixing ratio $\delta_{1\to2}$ of the $1^+_{sc} \to 2^+_1$ γ-ray transition of ^{156}Gd and ^{164}Dy has been measured using the linearly polarized photon beams of the HIγS facility. The employed method of photon-scattering experiments in combination with polarized, quasi-monochromatic beams and a dedicated detector setup is highly sensitive to the electric quadrupole-decay properties of the scissors mode.

1 Introduction

The study of the properties of the nuclear scissors mode [1–3] provides an essential insight into the nature of the restoring forces between the proton and neutron subsystems. Hence, the isovector low-lying $J^\pi_K = 1^+_1$ scissors mode of deformed nuclei has been studied extensively in the past with main focus on strong $M1$ transitions to the ground-state band [4, 5, and Refs. therein]. Despite the quadrupole-collective origin of the nuclear scissors mode, the $E2$ properties of the scissors mode were unknown until recently [6]. Likewise, information on the predicted existence of the scissors mode's rotational band with the $J = 1$ state as band head is limited [7, 8].

First information on the $E2$ decay transition strength of the scissors mode was extracted [6] from a high-statistics photon-scattering experiment on ^{156}Gd using quasi-monochromatic photon beams provided by the High Intensity γ-ray Source (HIγS) [9] at Duke University, Durham, NC, USA. The data allowed for measuring a finite value of the $E2/M1$ multipole mixing ratio and, thus, first measurement of an $E2$ transition between mixed-symmetric and a fully-symmetric states in axially deformed nuclei. The obtained results indicate that highest-precision photon-scattering experiments [4, 10] with linearly polarized photons [11] are highly sensitive to the electric quadrupole-decay properties of the scissors mode. It is the purpose of this manuscript to present first results obtained from a subsequent experiment on the well-deformed nucleus ^{164}Dy at HIγS.

2 Experimental details and results

The investigation of the $E2$ properties of the scissors mode is based on the well-known properties of the electromagnetic decay of the 1^+_{sc} scissors mode state to the 2^+_1 state. The linear polarization of the impinging photon beam causes an anisotropic azimuthal distribution of the scattered photons which is detected using the γ^3 setup [12]. It includes four high-purity Germanium (HPGe) detectors forming a setup which is especially sensitive to the $E2/M1$ mixing ratio

$$\delta_{1\to2} = \frac{\sqrt{3}}{10}\frac{E_\gamma}{\hbar c}\frac{\langle 2^+_1 \,\|\, \hat{T}(E2) \,\|\, 1^+_{\rm sc}\rangle}{\langle 2^+_1 \,\|\, \hat{T}(M1) \,\|\, 1^+_{\rm sc}\rangle} \quad (1)$$

of the $1^+_{sc} \to 2^+_1$ transition [13, 14]. Here, the multipole mixing ratio is given in the phase convention of Krane *et al.* [15]. The quantities $\hat{T}(E2)$ and $\hat{T}(M1)$ denote the electric quadrupole and magnetic dipole transition operators, respectively.

The ratio N_i/N_j of γ-ray intensities observed in detectors i and j is sensitive to the multipole mixing ratio $\delta_{1\to2}$ of the $1^+_{sc} \to 2^+_1$ transition. Subsequently, the multipole mixing ratio is obtained by comparison of the observed ratio to the respective ratio of angular distributions $W(\vartheta_i, \varphi_i, \delta_{1\to2})/W(\vartheta_j, \varphi_j, \delta_{1\to2})$ for the $0^+_1 \to 1^+_{sc} \to 2^+_1$ sequence. This method produces two equitable solutions; one close to zero, the other corresponding to dominant $E2$ character. Hence, further constraints based on the comparison of experimental decay intensity ratios to expectations from the Alaga rule [16] are needed to identify [6] the consistent solution for the multipole mixing ratio.

2.1 ^{156}Gd

The results of the pioneering experiment on ^{156}Gd are presented in detail elsewhere [6]. In the following, the robustness of the method towards systematic uncertainties shall be addressed.

Due to the compact geometry of the detector setup the angular distribution functions have to be integrated over the solid angles of the individual detectors considering the

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mean free path of 3 MeV photons in the detector material. The exact positioning of the target sample relative to the impinging γ-ray beam and the detector setup was achieved using a cross-line laser system. Nevertheless, an uncertainty contribution associated with a displacement of the target parallel to the beam axis remains and is estimated to be smaller than ±5 mm. Naturally, this results in altered solid angles of the respective detectors. However, for small values of the multipole mixing ratio $\delta_{1\to2}$ the resulting systematic uncertainty is of comparable size to the statistical uncertainty. Figure 1 shows the result for the multipole mixing ratio of the decay of the strongest fragment of the scissors mode of ^{156}Gd indicating the robustness of the method towards a displacement of the target sample along the beam axis.

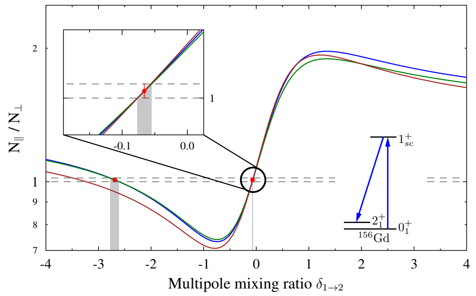

Figure 1. Comparison of the measured intensity ratio to the ratio of integrated angular distributions $W(135°, 0°, \delta_{1\to2})/W(135°, 90°, \delta_{1\to2})$ for the $0^+_1 \to 1^+_{sc} \to 2^+_1$ sequence indicated by the blue line. The two possible solutions for the multipole mixing ratio are marked in red. The brown and green lines mark the ratio of angular distributions integrated over the altered detector solid angles caused by a displacement of the target sample by ±5 mm in the direction of the γ-ray beam.

2.2 ^{164}Dy

Following the first successful application of the presented method, its advancement to cases with different detector setups and lower statistics is currently pursued. While the experiment on ^{156}Gd featured a polarimeter-like setup of four HPGe detectors at backward angles, an advanced geometry had been implemented for the measurement of the $E2$ decay of the scissors mode of ^{162,164}Dy. Two detectors were mounted at a polar angle of $\vartheta = 90°$ with respect to the incoming beam and at azimuthal angles φ of 0° and 90° with respect to the horizontal polarization plane. In addition, two HPGe detectors were placed at $(\vartheta, \varphi) = (135°, 225°)$ and $(135°, 315°)$, resulting in three unique detector combinations defined by the symmetry properties of the angular distribution functions.

Figure 2 shows the resulting ratios of integrated angular distributions $W(\vartheta_i, \varphi_i, \delta_{1\to2})/W(\vartheta_j, \varphi_j, \delta_{1\to2})$ for two detectors i and j as a function of the $E2/M1$ multipole mixing ratio. In the following, first results of the two detectors in polarimeter geometry, i.e. at a polar angle of $\vartheta = 90°$ and azimuthal angles φ of 0° and 90° corresponding to the blue curve of Figure 2, are presented.

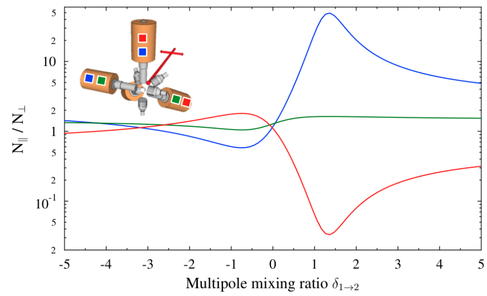

Figure 2. Evolution of the ratio of integrated angular distributions $W(\vartheta_i, \varphi_i, \delta_{1\to2})/W(\vartheta_j, \varphi_j, \delta_{1\to2})$ with the multipole mixing ratio of the $1^+_{sc} \to 2^+_1$ transition for different detector combinations color coded in the schematic setup (upper left corner). Due to the symmetry properties of the angular distribution functions three different detector combinations have to be considered.

The $(\vec{\gamma}, \gamma')$ spectra of ^{164}Dy measured in the polarization plane (red) and perpendicular to it (blue) are shown in Figure 3. The energy profile of the impinging γ-ray beam with a width of about 3.5% of the centroid energy 3.180 MeV is indicated by a dashed Gaussian. The decay of three scissors mode states to the ground state are prominently observed in the polarization plane corresponding to the red spectrum. Their mixed $E2/M1$ transition to the 2^+_1 state is found 0.073 MeV below, respectively.

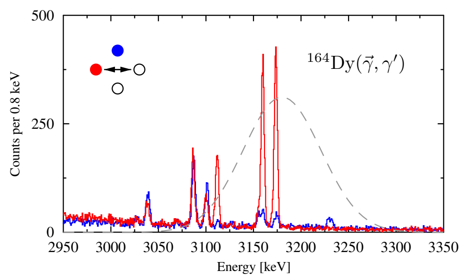

Figure 3. Gamma-ray spectra of the ^{164}Dy$(\vec{\gamma}, \gamma')$ reaction. Detectors were placed at a polar angle of $\vartheta = 90°$ and in the horizontal polarization plane (red) of the incident γ-ray beam and perpendicular to it (blue). The spectra are dominated by the decays of three scissors mode states to the ground state and to the 2^+_1 state. The energy profile of the $\vec{\gamma}$-ray beam is indicated by the dashed Gaussian curve.

For the 1^+_{sc} state located at 3.173 MeV a finite value of the multipole mixing ratio $\delta_{1\to2}$, which significantly differs from zero, is obtained from the $1^+_{sc} \to 2^+_1$ decay transition at 3.100 MeV. From the squared multipole mixing ratio $\delta^2_{1\to2} = \Gamma_{1^+_{sc}\to2^+_1,E2}/\Gamma_{1^+_{sc}\to2^+_1,M1}$ and the partial decay width $\Gamma_{1^+_{sc}\to2^+_1} = \Gamma_{1^+_{sc}\to2^+_1,M1} + \Gamma_{1^+_{sc}\to2^+_1,E2}$ [17] a preliminary transition strength $B(E2; 1^+_{sc} \to 2^+_1)$ well below 1 W.u. is determined. Naturally, the integration of the results of the remaining detector combinations (cf. Figure 2) will slightly alter this result.

3 Summary and Outlook

The results of ^{156}Gd and ^{164}Dy indicate that properties of the scissors mode's electric quadrupole decay can be obtained from highest-precision photon-scattering experiments with linearly polarized photons. However, further experiments are essential to shed light on the distribution of $E2$ strength compared to $M1$ strength in a single nucleus as well as its evolution with the number of valence neutrons.

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