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# A novel decay channel of the $1^+$ scissors mode: coupling to the vibrational $\beta$-excitation

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**Abstract.** The transitional nucleus $^{154}$Gd was investigated using a combination of a photon scattering experiment and a $\gamma\gamma$-coincidence study following the $\beta$ decay of $^{154}$Tb. A novel decay channel from the scissors mode to the band head of the $\beta$-band was observed. Its transition strength B(M1; $1^+_{sc} \rightarrow 0^+_\beta$) was determined. An IBM-2 calculation reveals a correlation of this decay channel and the shape phase transition between spherical and deformed nuclei.

## 1 Introduction

Quantum phase transitions in mesoscopic systems (finite number $N$ of particles) are of great interest in contemporary physics and are found in atomic nuclei, molecules, atomic clusters and finite polymers. The phase transitions occur between different geometric configurations or modes of collective motions. A convenient way to investigate phase transitions in mesoscopic systems are algebraic approaches, such as the interacting boson model (IBM) [1].

Atomic nuclei, which are composed of protons and neutrons, represent strongly coupled, two-fluid quantum systems. The nuclear scissors mode is the most prominent example of a collective valence shell excitation involving the proton-neutron degree of freedom. Therefore, it is desired to study those properties of the scissors mode that arise entirely from finite number effects of valence particles, such as electromagnetic transition rates to other intrinsic excitations. The scissors mode [1–4] is a low-lying magnetic dipole excitation, typically observed in deformed nuclei [5–7]. Within a geometrical picture the scissors mode is a counter oscillation of the deformed proton against the deformed neutron body in the intrinsic frame. According to the IBM-2 an enhanced M1 strength is a feature of an excitation in the proton-neutron (pn) degree of freedom.

Up to now, phase transition in nuclei were experimentally only investigated in symmetric states, where the proton and neutron wave functions couple in phase. Recently the influence of the pn degree of freedom on the phase transition was discussed theoretical [8–10]. For an experimental investigation of the pn degree of freedom at the shape phase transitional point X(5) [11] the study of the evolution of the scissors mode around the transitional point is an ideal test case. Therefore, the $N$ = 90 nucleus $^{154}$Gd

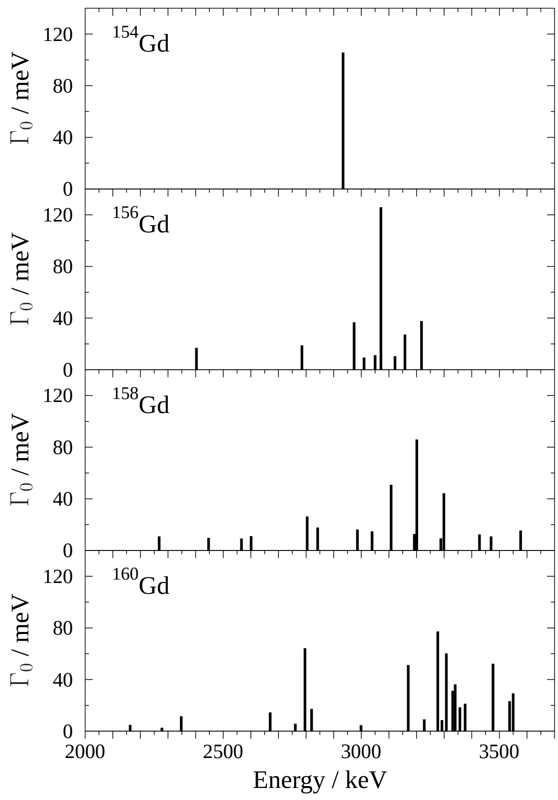


**Fig. 1.** Comparison of the ground-state transition widths $\Gamma_0$ for $\Delta K$ = 1 transitions. The data were obtained in electron scattering [12–14] and nuclear resonance fluorescence experiments [15]. These transitions are usually asumed to be of M1 character. For $^{154,156}$Gd the M1 strength is mainly concentrated in one level, while in $^{158,160}$Gd the strength is strongly fragmented.

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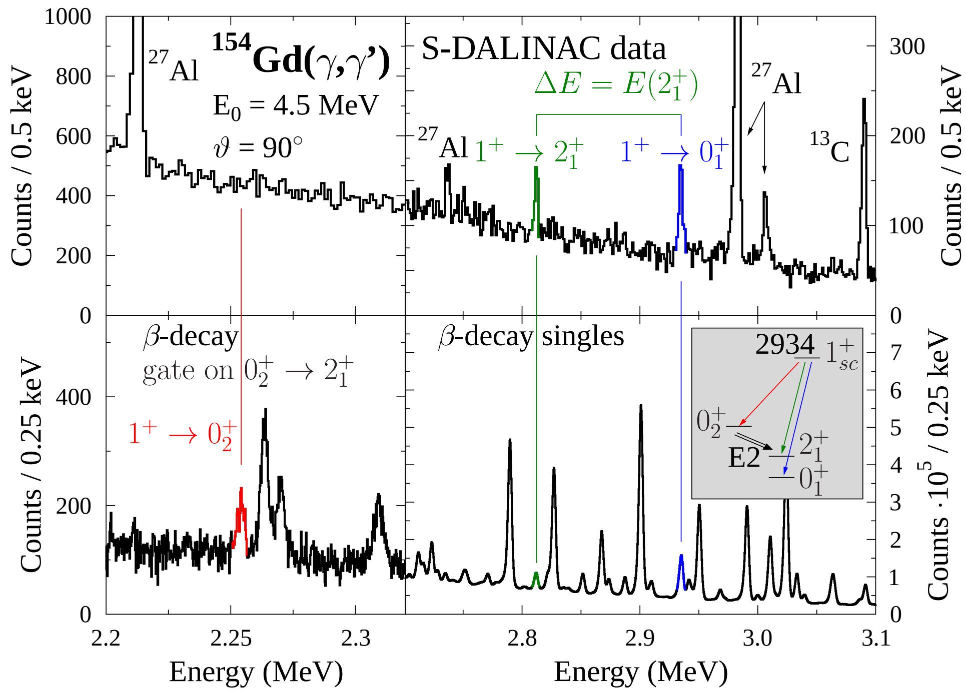


**Fig. 2.** (color online) Upper part: Photon scattering spectrum off $^{154}$Gd in the energy range of the scissors mode. At energies of 2811 and 2934 keV de-exciting transitions to the ground state and first $2^+$ of the strongly excited $1^+$ state are visible. Photon scattering cross sections are measured relative to well known [18] cross sections in $^{27}$Al, which is irradiated simultaneously (marked "Al"). Lower part: The right panel shows a part of the spectrum of $\gamma$ rays following the EC decay of the $0^+$ low-spin isomer of $^{154}$Tb$^m$. High statistics and low background allow for an observation of weak decay branches and to measure $\gamma\gamma$-coincidences for the decay of the scissors mode. The left panel shows a part of the $\gamma\gamma$-coincidence spectrum gated with the $0_2^+ \rightarrow 2_1^+$ transition. The coincident observation of the 2253 keV transition establishes the population of the $0_2^+$ state at 681 keV from the $1_1^+$ state at 2934 keV. Please note the different scaling of the y-axes.

was chosen. It was one of the first nuclei in which the scissors mode was observed [14]. In deformed nuclei a decay of the scissors mode to the $\beta$-band would annihilate the scissors-like oscillation while simultaneously exciting a $\beta$-vibration. Such two-phonon changing transitions are suppressed. They are forbidden by selection rules in geometrical models that correspond closely to the large boson-number limit of the IBM. Deviations from the selection rules may occur due to finite size effects.

A $\gamma$-decay of the scissors mode to other intrinsic excitations has so far not been reported. In this proceeding we report the first observation of a $\gamma$-ray transition between the scissors mode and the $\beta$-band head. This observation was accessible due to the combination of a $(\gamma,\gamma')$ experiment on $^{154}$Gd and a $\gamma\gamma$ coincidence measurement of transitions following the $\beta$ decay of $^{154}$Tb$^m$ to $^{154}$Gd. Combining these two techniques yields information about (a) lifetimes and spin quantum numbers from singles spectroscopy by resonant photon scattering and (b) small $\gamma$ branches from clean, off-beam $\gamma\gamma$-coincidence measurement. In favored cases $\beta$ decay strongly populates highly excited low-spin states among which we identify scissors mode states. The $1_{sc}^+$ scissors mode state at 2934 keV in $^{154}$Gd has the strongest M1-transition in the Gd isotopes (compare figure 1).

## 2 Experiments

The photon scattering experiment was performed at the Darmstadt High Intensity Photon Setup (DHIPS) [16] at the superconducting electron linear accelerator S-DALINAC at the TU Darmstadt. For bremsstrahlung production an electron beam with an energy of $E_{e^-} = 4.5$ MeV was used. The scattered photons were detected by three large-volume high-purity germanium (HPGe) detectors at 90° and 130° with respect to the incoming photon beam. The upper part of figure 2 shows the $(\gamma,\gamma')$ spectrum of $^{154}$Gd taken at incident photon energies $E_\gamma \leq 4.5$ MeV. The $1_{sc}^+$ scissors mode state at 2934 keV is strongly excited. Its decay to the $2_1^+$ is also clearly visible at 2811 keV. Its transition to the $\beta$-band head, which would be situated at 2253 keV, cannot be distinguished from the high background. The photon scattering cross sections $I_{s,f} = g\pi^2\lambda\!\!\!^-{}^2\Gamma_0\Gamma_f/\Gamma$ were measured, where $g = (2J+1)/(2J_0+1)$ is a statistical factor and $\lambda\!\!\!^- = \hbar c/E_x$ is the reduced scattering wavelength. $\Gamma$ and $\Gamma_0$ ($\Gamma_f$) are the total level width and the partial decay width to the ground (final) state. The total level width $\Gamma = \hbar/\tau$ is only accessible if all decay intensity ratios $\Gamma_i/\Gamma$ are known.

Decay intensity ratios $\Gamma_f/\Gamma$ were measured for low-spin states in $^{154}$Gd in a study of $\gamma$ rays following the $\beta$ decay of the $J^\pi = 0^+$ low-spin isomer, $^{154}$Tb$^m$. The Q-value of its electron capture reaction amounts 3.56(5) MeV. In contrast to the majority of nuclides for which information on the scissors mode exists this high EC-Q-value is sufficient for a population of the scissors mode in the daughter nucleus. This is the first time that the scissors mode was identified after $\beta$ decay. The $^{154}$Tb$^{m}$ nuclei were produced using the fusion evaporation reaction $^{154}$Gd(p,n)$^{154}$Tb$^{m}$ at an energy of $E_p = 12$ MeV. The proton beam was supplied by the FN Tandem Van de Graaff accelerator at the University of Cologne. The $\gamma\gamma$-coincidences were measured off-beam using the Cologne coincidence cube spectrometer HORUS [17]. The single spectrum between 2.7 and 3.0 MeV is shown in the right-hand side of the lower part of figure 2. The high counting rate, the low background in this off-beam measurement, and the isotropy of the $\gamma$ radiation after $\beta$ decay allowed for a precise determination of the intensity ratios $\Gamma_f/\Gamma$. The $2^+_1 \rightarrow 0^+_1$ transition amounts $1.9 \cdot 10^9$ counts in singles and $144 \cdot 10^6$ counts in coincidence mode. The left-hand side of the lower part of figure 2 shows the 2253 keV transiton in the spectrum, which was observed in coincidence with the $0^+_2 \rightarrow 2^+_1$ transition. The 2253 keV transition populates directly the $0^+_2$ state at 681 keV from the $1^+_{sc}$ state at 2934 keV. This is the first identification of such a transition.

Since the 2253 keV is not visible in the single spectrum due to the high density of transitions, the decay intensity ratio cannot be measured directly. However, exploiting a transition which populates the $0^+_2$ state with high intensity ($J^\pi_i \rightarrow 0^+_2$) we can determine the decay intensity ratio $\Gamma_f/\Gamma_0$ by combining the intensity ratio $I(1^+_{sc} \rightarrow 0^+_2)/I(J^\pi_i \rightarrow 0^+_2)$ measured in coincidence to the $0^+_2 \rightarrow 2^+_1$ transition and the intensity ratio $I(J^\pi_i \rightarrow 0^+_2)/I(1^+_{sc} \rightarrow 0^+_1)$ measured in the single spectrum.

$$\Gamma_f/\Gamma_0 = \frac{I(1^+_{sc}\rightarrow 0^+_2)}{I(1^+_{sc}\rightarrow 0^+_1)} = \left(\frac{I(1^+_{sc}\rightarrow 0^+_2)}{I(J^\pi_i\rightarrow 0^+_2)}\right)_{coinc.\ to\ 0^+_2\rightarrow 2^+_1} \cdot \frac{I(J^\pi_i\rightarrow 0^+_2)}{I(1^+_{sc}\rightarrow 0^+_1)}$$

The partial decay widths $\Gamma_f$, total level width $\Gamma = \sum \Gamma_f$, the level lifetime $\tau = \hbar/\Gamma$, and transition rates $w_f = \Gamma_f/\hbar$ were determined by combining the measured photon scattering cross sections $I_{s,f} \propto \Gamma_0\Gamma_f/\Gamma$ and the decay intensity ratios $\Gamma_0/\Gamma$ from the $\beta$ decay experiment. The measured, partial, single-multipolarity decay widths $\Gamma_{f,\pi\lambda}$ are proportional to the reduced transition strengths $B(\pi\lambda)$. The analysis is ongoing.

## 3 Discussion

To describe nuclei near the shape-phase transition and to also to include the pn degree of freedom the model of choice is the IBM-2. In this framework it is possible to investigate the transitional region and the scissors mode simultaneously. Therein a reasonable ansatz for the Hamiltonian is:

$$\hat{H}_{IBM} = \epsilon \cdot \hat{n}_d + \kappa \cdot \hat{Q}_\pi^{\chi} \cdot \hat{Q}_\nu^{\chi} + \frac{1}{2}\sum_{L=0,2}(c_\pi^{(L)}\left[d_\pi^\dagger d_\pi^\dagger\right]^{(L)} \cdot [d_\pi d_\pi]^{(L)} + \lambda \hat{M}_{\pi\nu}$$

where $\hat{n}_d$ denotes the number of d-bosons, $\hat{Q}_\pi^{\chi}$ ($\hat{Q}_\nu^{\chi}$) the proton (neutron) quadrupole operator and $\hat{M}_{\pi\nu}$ the Majorana operator. The parameters were adjusted in such a way that main characteristics of the experimental level scheme and transition probabilities were reproduced. Figure 3 shows a comparison between the IBM-2 calculation for $^{154}$Gd and the experimental results. While the energy

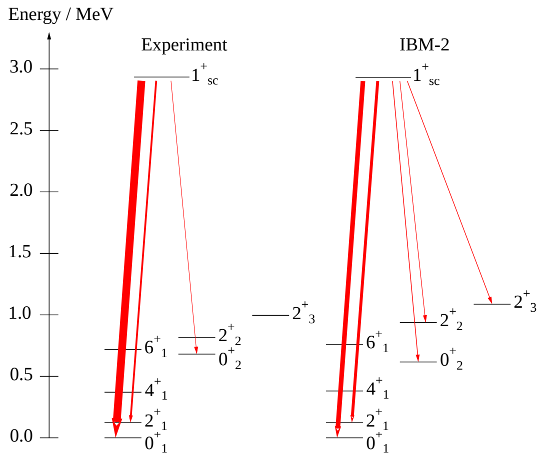


**Fig. 3.** (color online) Comparison of the experimentally known low-energy levels of $^{154}$Gd and the $J^\pi = 1^+$ scissors mode state with an IBM-2 calculation. The depopulating transitions of the scissors mode to other levels is shown. The thickness of the arrows scales with the transition strength. The left part shows the experimental values and the right part the results of an IBM-2 calculation. Energy eigenvalues and transition strengths are in a fairly good agreement with the experimental values.

eigenvalues are in satisfactory agreement the IBM-2 is not capable of describing decay branchings of the $J^\pi = 1^+$ scissors mode state correctly. The M1 transition strengths do not match with the experimental values. In addition the calculation predicts also decay branches from the scissors mode to the $2^+_2$ ($2^+_\beta$) and $2^+_3$ ($2^+_\gamma$) which could not be verified experimentally. These observations raise the question whether the Majorana operator in this one-parameter form is capable to describe the nuclear scissors mode and its properties.

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