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SEARCH FOR FINGERPRINTS OF TETRAHEDRAL SYMMETRY IN ^{156}Gd*

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Theoretical predictions suggest the presence of tetrahedral symmetry as an explanation for the vanishing intra-band E2 transitions at the bottom of the odd-spin negative-parity band in ^{156}Gd. The present study reports on experiment performed to address this phenomenon. It allowed to remove certain ambiguouities related to the intra-band E2 transitions in the negative-parity bands, to determine the new inter-band transitions and reduced probability ratios $B(\mathrm{E2})/B(\mathrm{E1})$ and, for the first time, to determine the experimental uncertainties related to the latter observable.

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1. Introduction

It has been suggested on the basis of the realistic nuclear mean-field calculations, Ref. [1], that there should exist atomic nuclei whose shapes are tetrahedral-symmetric. Theoretical calculations, Ref. [2] and references therein, suggest that to a first approximation, the nuclei whose shapes are characterized by the exact tetrahedral symmetry have vanishing multipole moments except for the $Q_{3\pm2}$ one, the next order multipoles allowed by the tetrahedral symmetry are $Q_{7\pm2}$ and $Q_{7\pm6}$ and such contributions are expected to be very small if not totally negligible in the nucleus studied. Thus, unlike in rotational bands of quadrupole-deformed nuclei where the E2 transitions dominate, in tetrahedral bands the E2 transitions are predicted to vanish or to be very weak, because the quadrupole moments go to zero when the tetrahedral symmetry becomes exact. According to ENSDF, Ref. [3], the nucleus ^{156}Gd has been studied in over 15 different excitation modes with varying target-beam combinations, beam energies, and detection systems. Although a regular sequence of odd-spin negative-parity states has been established down to $I^{\pi} = 3^{-}$, the intra-band E2 transitions below the $I^{\pi} = 9^{-}$ state have never been seen. The energies of the corresponding states have been measured exclusively through the inter-band E1 transitions to the ground-state band. Such a behavior is expected to be a consequence of tetrahedral symmetry [2]. Already in the early eighties, Konijn and co-workers, Ref. [4], carried out an experiment using an α-particle beam and measured the ratios of the reduced transition strengths, $B(\mathrm{E2})/B(\mathrm{E1})$, for two negative-parity bands in ^{156}Gd — at that time interpreted as octupole vibrational bands. The $B(\mathrm{E2})/B(\mathrm{E1})$ ratios were found to be about a factor 50 lower in the odd-spin, as compared to those in the even-spin negative-parity bands. More recently, Sugawara, Ref. [5], measured the branching ratios of these two negative-parity bands by using the reaction ^{150}Nd(^{13}C,$\alpha 3n$). In the case of the odd-spin negative-parity bands, a minimum in the $B(\mathrm{E2})/B(\mathrm{E1})$ ratios at intermediate spins was reported and some upper limits of branching ratios at low spins were measured. These measurements have been carried out at best by using the γ–γ coincidences with a population of ^{156}Gd that may not have been enough to observe the low-intensity transitions. The main goal of this experiment was to search for the E2 transitions forbidden by the tetrahedral symmetry with high statistics, to determine the $B(\mathrm{E2})/B(\mathrm{E1})$ ratios, and to search for any signs of cross-feeding involving the odd-spin negative-parity band.

2. Experiment

The nucleus ^{156}Gd was produced by using the fusion-evaporation reaction $^{154}\mathrm{Sm}(\alpha, 2n)$ and then studied by using the JUROGAM γ-ray detector, Ref. [6], at Jyväskylä. The optimal bombarding energy (27 MeV) was deduced from the excitation function measured for this reaction at the Orsay Tandem during a pilot experiment. This bombarding energy enabled us to optimize the population at low and medium spins in ^{156}Gd and to minimize the contaminations from other channels (*e.g.* mainly ^{155}Gd) below 8%. In this experiment, 43 Anti-Compton suppressed HP-Ge detectors were used, giving a total photopeak efficiency of 4.2%. We used self-supporting, 99.2% enriched, ^{154}Sm targets with a thickness of 2 mg/cm^2. The acquisition was performed by both analogue and digital system in trigger-less mode. The TNT2 digital acquisition cards from the IPHC, Strasbourg, were used to record data from prompt gamma-ray emissions from the Germanium detectors. The digital acquisition allows a higher count-rate (up to 100 kHz) due to shorter deadtime [7]. The digitization of the ADC pulse via the Jordanov algorithm [8] provides a stable energy measurement and fast baseline restoration. These features provide access to a wider range of beam intensities and therefore to phenomena with lower cross sections. At a similar count-rate, the digital acquisition records 36% more statistics than the analogue system and shows a better linearity in energy, specifically under 300 keV. In our study, a total of 228×10^6 $\gamma\gamma\gamma$ coincidence-events have been collected (*i.e.* pure unfolded coincidences after Compton-suppression).

3. Results

A partial level scheme of ^{156}Gd, established in this work, is displayed in Fig. 1. For the odd-spin negative-parity band we confirm that the E2

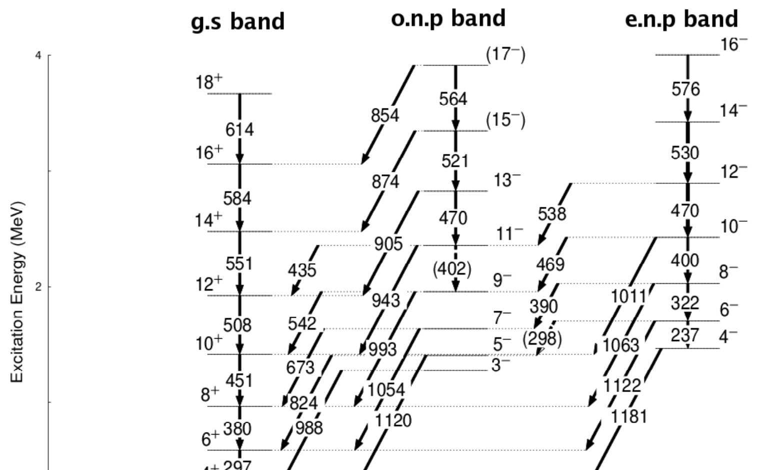

Fig. 1. Partial decay scheme of ^{156}Gd showing the ground-state band, odd- and and even-spin negative parity bands; the newly established interconnecting transitions are shown (see the text).

transitions vanish below the $I^\pi = 9^-$ state. The intensity of the $11^- \to 9^-$ transition is very weak and could not be firmly established. In fact, this transition is a part of a doublet (400–402 keV) in coincidences with another doublet at 470 keV both present in the odd-spin band and the even spin band. Therefore gating on the 470 keV line to extract the 402 keV intensity would bring in any case residual contamination from the 400 keV line. The E1 transitions de-exciting the $I^\pi = 1^-$ state and the E2 transition connecting the $4^- \to 2^-$ (reported in previous experiments) from the even-spin band cannot be confirmed by our results. However, $\gamma\gamma\gamma$ coincidences allowed us to clarify a number of uncertainties caused by the presence of doublet- and even triplet-lines in the spectrum of this nucleus. Moreover, we were able to examine the transitions in the medium spin range and firmly establish new inter-band transitions with E_γ of 538, 469 and 390 keV. Angular distributions will be analysed in the near future to determine the character (stretched M1 or non-stretched E2) of these transitions. Table I shows some preliminary $B(\mathrm{E2})/B(\mathrm{E1})$ ratios that we have found, compared to the results of the previous studies of Refs. [4, 5]. For the 15^- and 13^- states of the odd-spin negative-parity band, the transition strength ratios are of the same order of magnitude as previously reported, while for higher spin states they could not be determined because of the cut-off in angular momentum due to the use of the α-beam. Only upper limits are established for the lowest spins, however this information represents already a progress since no earlier publication quotes any estimates for the $(9^- \to 7^-)$ and $(7^- \to 5^-)$ transitions. For the even-spin negative-parity band the $B(\mathrm{E2})/B(\mathrm{E1})$ ratios decrease with decreasing spin and are up to two orders of magnitude higher than those of the odd-spin negative-parity band.

TABLE I

Branching ratios $B(\mathrm{E2})/B(\mathrm{E1})$ in units $10^6\mathrm{fm}^2$. (a) Established in the present work — in comparison with: (b) Previous results from Refs. [4, 5].

I^π	$B(\mathrm{E2})/B(\mathrm{E1})$ (a)	$B(\mathrm{E2})/B(\mathrm{E1})$ (b)	I^π	$B(\mathrm{E2})/B(\mathrm{E1})$ (a)	$B(\mathrm{E2})/B(\mathrm{E1})$ (b)
17^-	—	16(3)	12^-	—	
15^-	4.5(1.0)	6(2)	10^-	640(100)	240
13^-	5.5(0.6)	7(2)	8^-	330(10)	700
11^-	<9(−2)	15(7)	6^-	210(15)	350
9^-	<26(−5)		4^-	—	
7^-	<92(−11)				
5^-	—				

4. Conclusions and discussion

The vanishing of intra-band E2 transitions, supporting the tetrahedral symmetry interpretation at the bottom of the odd-spin negative-parity band, has been confirmed along with the two-orders-of-magnitude differences in the $B(\mathrm{E2})/B(\mathrm{E1})$ branching ratios of two negative-parity bands. Thanks to the $\gamma\gamma\gamma$ coincidences, we have established new inter-band transitions. As it is known from general considerations, *cf.* Ref. [9], a $K^\pi = 0^-$ band must not have even spins and it follows that the even-spin negative-parity band discussed here must not be interpreted as 0^-, in contrast to some first claims in the past. We were not able to establish the $4^- \to 2^-$ transition which most likely signifies that it is very weak or non-existent. Therefore, it will be even more important to find-out whether the $\Delta I = 1$ transitions connecting the even- and odd-spin negative-parity bands have the $M1$-character, which could suggest the presence of high-K components in the underlying bandheads.

Let us emphasize at this point that the tetrahedral configurations, as predicted by theory, are markedly non-axial and, therefore, are expected to strongly mix components of wave-functions with various quantum numbers K: the strongest component associated with the geometry of shapes based on the $Y_{3+2} + Y_{3-2}$ spherical harmonics should be $K = 2$. Theoretical calculations based on the generalised collective rotor Hamiltonian that includes terms of the third order in angular momentum[1] indicate that the structure of the wave-function of the 1^- state is exceptional since, in contrast to states with $I \geq 2$, it *must not manifest* the tetrahedral symmetry. In other words, for $I \leq 1$ the tetrahedral symmetry is excluded; actually 1^- state wave-function manifest an axial symmetry. Consequently, the role of the 1^- state, often treated as a member of the (expected to be) the tetrahedral band, is special in that even if connected to the 3^- state via an E2 transition, in principle possible due to an expected to be strong a K-mixing, its underlying symmetry must not be tetrahedral. Our experiment, similarly to the preceding ones, gives no sign of the $3^- \to 1^-$ transition neither, what signifies that the corresponding E2 transition, if exists, must be very weak.

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[1] Hamiltonians of order higher than two in terms of the angular momentum operators are commonly used in molecular physics to describe the geometrical molecular symmetries.

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