RE-MEASUREMENT OF REDUCED TRANSITION PROBABILITIES IN ^{132}Ba*

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Reduced transition probabilities between the low-lying states of ^{132}Ba were measured using the Coulomb excitation technique. The experiment was performed at Inter University Accelerator Center (IUAC), New Delhi using a ^{58}Ni beam of 175 MeV energy to Coulomb excite the ^{132}Ba nuclei. In addition to the 2_1^+ state, other states in ^{132}Ba, such as 2_2^+ and 4_1^+, were populated, the latter for the first time using Coulomb excitation. A set of matrix elements was extracted for the transitions between these levels. These values were determined relative to ^{134}Ba excitations to minimize the systematic errors. A $B(\mathrm{E2};\ 0_{\mathrm{gs}}^+ \to 2_1^+)$ value of 1.088(85) $e^2\mathrm{b}^2$ was determined, corresponding to ~ 54.5 single-particle units.

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1. Introduction

Nuclei around magic Sn isotopes have been the central region of studies for a long time. Available data for neutron-rich tin isotopes are now being complemented by those for the neighbouring isotopic chains, having valence

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protons and neutrons [1–3]. In the $A \approx 130$ mass region, a transition from vibrational character to triaxial deformation has been observed [4, 5] and hence these nuclei are of much interest for nuclear structure studies. These nuclei ($Z \geq 52$, $50 \leq N \leq 82$) are also a good test case for validations of various models and lie in the region where proton–neutron interactions inside the nucleus are well enhanced, and hence must be studied profoundly. Stable barium isotopes ($Z = 56$), lying in the rare-earth mass region, have six more protons than the magic number $Z = 50$, with neutron number varying from $N = 74$ to $N = 82$. These isotopes cover a transitional region, stretching from ^{130}Ba displaying a rotational character at $N = 74$ to ^{138}Ba having a spherical shape for a closed neutron shell at $N = 82$. $R_{4/2}(= E_{4_1^+}/E_{2_1^+})$ value, which is a good indicator of collectivity, decreases sharply with N from the O(6) to SU(5) limit [6, 7].

In recent years, several microscopic and algebraic models were applied to these nuclei, *viz.* General Bohr Hamiltonian [8], Monte Carlo Shell Model [9], and Interacting Boson Model (IBM-2) [10]. However, experimental data for ^{132}Ba is scarce as compared to other neighboring isotopes [11]. The previous measurements with ^{132}Ba were performed long back in 1958 and 1985 by Fagg *et al.* [12] and Burnett *et al.* [13] respectively. Fagg *et al.* used $\sim$ 5.6 MeV alpha particles from the NRL large Van der Graaf generator to Coulomb excite the Ba isotopes in a $BaCl_2$ target ($\approx 12\%$ enriched in ^{132}Ba) encapsulated in planchets of stainless steel/tin. Burnett *et al.* used a ^{12}C beam of 40 MeV energy on a $BaCl_2$ target, which is well above Cline's safe energy [14], and hence the influence of nuclear interactions cannot be neglected while determining the reduced transition probabilities. Also, the previous Coulomb excitation studies did not populate the 4_1^+ state in ^{132}Ba.

2. Experimental details

The present experiment was performed in the Gamma Detector Array (GDA) beam-line at Inter University Accelerator Center (IUAC), New Delhi. A ^{132}Ba target of thickness $\sim 650\ \mu\text{g/cm}^2$ (with 40.7% isotopic enrichment) on carbon backing of $\sim 30\ \mu\text{g/cm}^2$ [15] was used in the experiment. The thickness of the target was determined by weighing and α-transmission measurements. ^{58}Ni beam at 175 MeV energy from the 15 UD tandem accelerator bombarded the target to Coulomb excite the Ba nuclei. The beam energy was well below Cline's safe energy limit for this system [14]. The scattered beam particles and the recoils were detected in an indigenously developed annular gas-filled parallel plate avalanche counter (PPAC) [16], position sensitive for both the azimuthal (ϕ_p) and polar (θ_p) angles. The particle detector was placed in the forward direction from the target position, covering an angular range of $15^\circ \leq \theta_{\text{lab}} \leq 45^\circ$ in the laboratory frame.

The azimuthal (ϕ_p) angle was obtained from the anode foil which was divided into 16 radial sections of 22.5° each. The polar (θ_p) angle was determined from the cathode which was patterned in concentric conductor rings of constant θ, each 1 mm wide, with insulating gaps of 0.5 mm between them. Each ring was connected to its neighbor by a delay line of 2 ns. A constant flow of isobutane at $\sim$ 10 mbar pressure was maintained inside the PPAC detector during the experiment. The de-exciting γ rays were detected in four Clover detectors, having an energy resolution of about 2.5 keV (at 1408 keV), mounted at angle (θ_γ) $\sim$ 145° relative to the beam direction. The ϕ_γ angles for the clover detectors were $\pm$45° and $\pm$145° relative to the vertical direction. Individual energies and timings from the 16 crystals were recorded in coincidence with the PPAC cathode (16 signals) event-by-event. Cu, Sn, and Pb absorbers of thickness between 0.5 and 0.7 mm were placed in front of the Clover detectors to suppress the low-energy radiation. Scattered ^{58}Ni ions and Ba recoils could not be distinguished with the particle detector, but they correspond to different ranges of centre-of-mass scattering angles, *i.e.* $21.5° \leq \theta_{\rm cm} \leq 63.1°$ for Ni detection and $90° \leq \theta_{\rm cm} \leq 150°$ for Ba detection. Energy calibrations and efficiency measurements for each crystal of the Clover detectors were carried out using a standard ^{152}Eu source.

3. Results and data analysis

The data was analyzed using the GSI Object Oriented On-line Off-line (GO4) software package [17]. Individual timing gates were applied for each crystal of the Clover detectors and phi segments of the PPAC to reduce the background radiation. The information of azimuthal angle (ϕ_p) was obtained by detecting the hit pattern in the azimuthal sector of the PPAC and the scattering angle (θ_p) was obtained from the time difference between the inner and outer readouts of the delay lines.

Doppler-shift correction of the measured γ-ray energies was performed event-by-event using the information on scattering angles and a Clover detector positions. A γ-ray energy resolution of about 1% was obtained after a Doppler-shift correction for the projectile detection. A Doppler-shift corrected γ-ray spectrum for a single crystal of a Clover detector is shown in Fig. 1 for the case of distant collisions *i.e.* ^{58}Ni projectiles detected in the particle detector. The intensities of the γ-ray lines corresponding to the $2^+_1 \to 0^+_{\rm gs}$ transitions in this spectrum are directly related to the $B({\rm E2};\, 0^+_{\rm gs} \to 2^+_1)$ values in ^{132}Ba and ^{134}Ba, assuming that the quadrupole moments of the 2^+_1 states are equal to zero. The experimental γ-ray yields were corrected for the individual efficiencies of different Ge crystals of the Clover detectors and target enrichment. In order to minimize the systematic errors, the $B({\rm E2};\, 0^+_{\rm gs} \to 2^+_1)$ value in ^{132}Ba was determined relative to the $B({\rm E2};\, 0^+_{\rm gs} \to 2^+_1)$ value in ^{134}Ba equal to 0.679(11) $e^2{\rm b}^2$ [18].

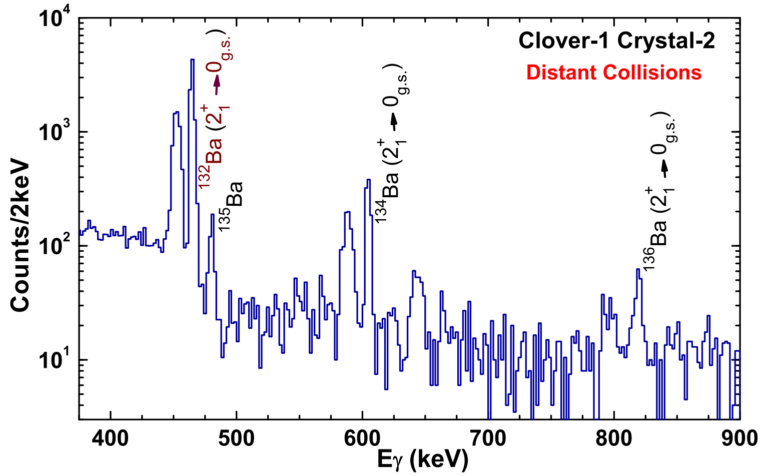

Fig. 1. Doppler-shift corrected γ-ray spectrum for a single crystal of a Clover detector, measured in coincidence with scattered ^{58}Ni detected in the PPAC.

We could also observe other higher-lying excited states in ^{132}Ba for the case of close collisions (target recoil detected in the PPAC), as shown in Fig. 2. Due to the isotopic contamination of the target, we could also observe the first excited states of other Ba isotopes *i.e.* ^{134,135,136,138}Ba. As shown in Figs. 1 and 2, the detected γ rays corresponded to two different scattering kinematics *i.e.* distant collisions (projectile detection) and close collisions

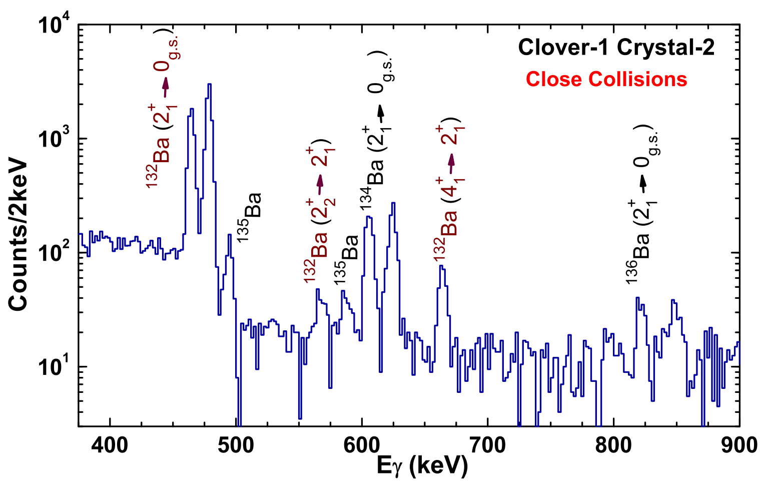

Fig. 2. Doppler-shift corrected γ-ray spectrum for a single crystal of a Clover detector, measured in coincidence with Ba recoils detected in the PPAC.

(target detection), however, at a time only one kinematics could be corrected for the Doppler broadening (for details, see Ref. [3]) which resulted in double peak structures observed for the $2^+_1 \to 0^+_{\rm gs}$ transitions in Ba isotopes.

The Coulomb excitation calculations were performed using the Winther–de Boer Coulomb excitation code [19]. The matrix elements were optimized by following the procedure given in Refs. [3, 20] to reproduce the experimental γ-ray yield ratios. In the present measurement, we could not detect the $2^+_2 \to 0^+_{\rm gs}$ transition, however, the $2^+_2 \to 2^+_1$ decay was observed, as shown in Fig. 2. Therefore, in order to extract the $B({\rm E2};\ 0^+_{\rm gs} \to 2^+_2)$ value, the branching ratio $(2^+_2 \to 0^+_{\rm gs})/(2^+_2 \to 2^+_1)$ from Ref. [21] was used. The newly extracted $B({\rm E2}\uparrow)$ values along with the previously reported values [13] are listed in Table I.

TABLE I

Comparison of the $B({\rm E2}\uparrow)$ values in ^{132}Ba deduced from the present experiment with those from the previous Coulomb excitation measurement [13].

Transition $I_{\rm i} \to I_{\rm f}$	$B({\rm E2}\uparrow)$ $[e^2{\rm b}^2]$ Present	Ref. [13]
$0^+_{\rm gs} \to 2^+_1$	1.088 ± 0.085	0.86 ± 0.06
$2^+_1 \to 4^+_1$	1.563 ± 0.134	—
$2^+_1 \to 2^+_2$	1.334 ± 0.181	0.58 ± 0.06
$0^+_{\rm gs} \to 2^+_2$	0.036 ± 0.007	0.073 ± 0.003

4. Summary and conclusions

A multi-step Coulomb excitation experiment was performed at IUAC, New Delhi. The transition matrix elements were extracted using the Winther–de Boer Coulomb excitation code [19]. The $B({\rm E2};\ 0^+_{\rm gs} \to 2^+_1)$ value for ^{132}Ba was calculated with respect to that of ^{134}Ba which was present as an isotopic contamination in the target. The $B({\rm E2};\ 2^+_1 \to 4^+_1)$ value was measured for the first time. Recent shell model calculations [22] reported a $B({\rm E2}\downarrow; 2^+_1 \to 0^+_{\rm gs})$ value of 53.1 W.u. which is in agreement with our measured value of 54.5 ± 4.3 W.u.

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