INVESTIGATION OF AN INTRUDER BAND IN ^{45}Sc VIA COULOMB EXCITATION*

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In order to gain further information on the electromagnetic properties of the low-lying states in ^{45}Sc, a Coulomb excitation measurement was carried out at the IUAC, New Delhi. The ^{45}Sc target nuclei were Coulomb excited by the 70 MeV ^{32}S beam from the 15UD tandem accelerator. The γ-rays depopulating Coulomb excited states in ^{45}Sc were detected by four Clover detectors in coincidence with the forward scattered ions. The main aim of the experiment was to determine the $B(\mathrm{E3}; 7/2^- \to 3/2^+)$ and $B(\mathrm{E3}; 7/2^- \to 5/2^+)$ transition probabilities, as well as the transitional electromagnetic matrix elements for low-lying intruder states.

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1. Introduction

Nuclei in the middle of the $f_{7/2}$ shell are shown to have rotational features. Although in this region the ground states are predominantly spherical, at higher values of spin well-deformed rotational bands are present. This nuclear region turned out to be a privileged one as Large-Scale Shell Model (LSSM) calculations for natural parity states in the full fp configuration space get, in general, very good agreement with experimental data [1–3]. Superdeformation resulted from the multiple particle–hole excitations across the magic $N = Z = 20$ shells was discovered in ^{36,38,40}Ar, ^{40,42}Ca and ^{44}Ti [4–9].

The ^{45}Sc nucleus, situated in the nuclear chart above doubly magic ^{40}Ca, has additional 1 proton and 4 neutrons beyond the $Z = N = 20$ shell closure. The negative-parity states built on the $7/2^-$ ground state exhibit a spherical structure, while a well-deformed rotational-like band is formed upon the $3/2^+$ intruder level at 12.4 keV [10–13]. Our attention is addressed to the positive parity band built on the low-lying $T_{1/2} = 318$ ms isomeric state at the energy of 12.4 keV and spin $3/2^+$. In the collinear laser spectroscopy measurement [13], the electric quadrupole moment $Q_s = 0.28(5)$ b for the $3/2^+$ isomeric state was obtained; this result corresponds to a prolate deformation with the elongation parameter $\beta \sim 0.3$. There were also Coulomb excitation measurements with beams of ^{16}O and ^{35}Cl ions in the early 1970s [14, 15]. In these measurements, properties of the first and second excited states were studied, and the upper limit of 2.7 single-particle units for the E3 transition probability $B(\mathrm{E3}; 7/2^- \to 3/2^+)$ was extracted [14].

Completing the missing properties of the low-lying states in ^{45}Sc, which can be obtained from the Coulomb excitation studies, such as sign and magnitude of quadrupole moment for the $5/2^+$ state at 543 keV, as well as the transitional electromagnetic matrix elements between low-lying states, will contribute towards a better understanding of the role played by single-particle degrees of freedom in creating nuclear collectivity.

To study electromagnetic properties of the low-lying states in ^{45}Sc, the Coulomb excitation experiment was performed at the Heavy Ion Laboratory, University of Warsaw (HIL UW), using a 70 MeV ^{32}S beam and a thick 15 mg/cm^2 ^{45}Sc target [16]. For the analysis of collected data, least square fitting code GOSIA was used [17]. Measured γ-ray intensities together with existing spectroscopic data (such as excited-state lifetimes, E2/M1 mixing ratios and γ-ray branching ratios) were used to extract a set of matrix elements for transitions between the populated states.

In addition, the upper limit of 1.7 W.u. for the $B(\mathrm{E3}; 7/2^- \to 5/2^+)$ reduced excitation probability, from the ground state to the $5/2^+$ at 543 keV, was given. In order to gain further information on the electromagnetic properties of the low-lying states in ^{45}Sc and to disantangle contributions from the $B(\mathrm{E3}; 7/2^- \to 3/2^+)$ and $B(\mathrm{E3}; 7/2^- \to 5/2^+)$ transition probabilities, a complementary measurement was performed at the Inter-University Accelerator Centre (IUAC) in New Delhi.

2. Experiment

The Coulomb excitation measurement of ^{45}Sc was performed in November 2017 using a 70 MeV ^{32}S beam from the 15UD tandem accelerator at IUAC, New Delhi. The ^{32}S beam particles were scattered on a 1 mg/cm^2 ^{45}Sc target. The γ-rays depopulating Coulomb excited states in ^{45}Sc were detected by the four Clover detectors in coincidence with forward scattered ions. The scattered beam particles and the recoiling target nuclei were detected in the position sensitive Annular Parallel Plate Proportional Counter APPPC [18], placed in the forward direction covering scattering angles: $\theta_{\mathrm{LAB}} = 15°$–$45°$ and $\phi_{\mathrm{LAB}} = 0°$–$360°$. The gas-filled APPPC particle detector is position sensitive in θ and ϕ angles. The front layer was divided into 16 radial sections to provide ϕ angle, whereas the backward placed delay lines provide θ scattering angle of the reaction products. The Clover detectors were placed at the backward angle $\theta_{\mathrm{LAB}} \sim 145°$ relative to the beam direction. For the given configuration, in the forward kinematics, the opening angle of the APPPC corresponds to an angular coverage of $\theta_{\mathrm{CM}} = 25°$–$75°$ for projectile and $\theta_{\mathrm{CM}} = 105°$–$155°$ for target nuclei, in the center-of-mass system.

3. Analysis

Collected data were analyzed using GSI Object Oriented (Go4) software package [19]. Individual timing gates were applied for each crystal of Clover detectors and ϕ segments of APPPC to reduce the background radiation. Collected γ-ray energy spectrum for all crystals in coincidence with all APPPC segments were Doppler corrected for the projectile ions detected in particle detector (see Fig. 1). The most intense γ-ray lines originating from the Coulomb excited states in ^{45}Sc are marked.

The double-peak structure seen in Fig. 1 results from the fact that in the given configuration, both kinematics are registered. One peak component arises from the distant collision events and the second one from the close collision events.

Figure 2 shows a typical Ge crystal spectrum summed for the particle detector segments, for which both peaks originating from different kinematics were well-separated (in that case 7 segments were taken into account, covering angular range from $0°$–$22.5°$ and $225°$–$360°$). Spectrum marked in black was Doppler corrected for particle ions detected in APPPC and target excited (distant collision), whereas gray/red spectrum was Doppler corrected for target recoils detected in APPPC and target excited (close collision).

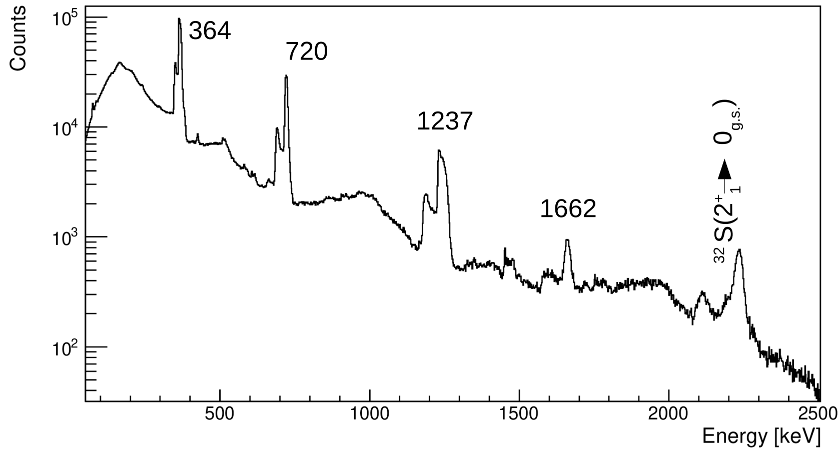

Fig. 1. Total γ-ray energy spectrum following Coulomb excitation of ^{45}Sc, Doppler corrected for the projectile ions detected in APPPC. Peaks are marked with their energy in keV.

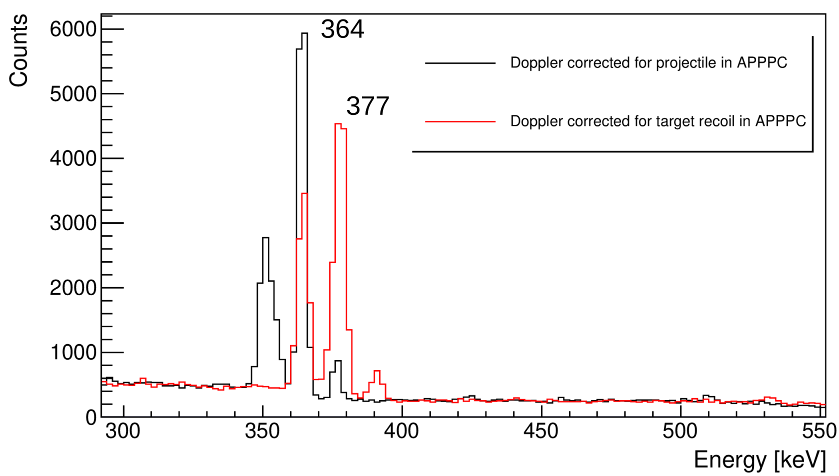

Fig. 2. (Color online) γ-ray deexcitation spectra associated with Coulomb excitation of ^{45}Sc, Doppler corrected for the projectile ions detected in APPPC (black) and target recoils (gray/red). Spectra for only one Ge crystal and 7 segments of particle detector. Peaks are marked with their energy in keV.

The beam energy (70 MeV) was chosen to maximize the excitation probability of the low-lying states in ^{45}Sc. However, the Cline's "safe energy" criterion ensuring the purely electromagnetic interaction between the colliding nuclei [20] was fulfilled only for the forward kinematics, up to scattering angle $\theta_{\rm LAB} = 65^\circ$ in the laboratory system. Therefore, for the analysis, we are selecting those combination of crystals and APPPC segments in which this double peak structure is well-separated to take into account only cases resulting from the "safe" Coulomb excitation. Such a spectrum is presented in Fig. 3, it contains γ-rays registered in coincidence with particles detected at:

— Clover1 ($\theta_\gamma \sim 145°$, $\phi_\gamma \sim 45°$) and $\phi_p = 135°$–$270°$;

— Clover2 ($\theta_\gamma \sim 145°$, $\phi_\gamma \sim 145°$) and $\phi_p = 90°$–$202.5°$;

— Clover3 ($\theta_\gamma \sim 145°$, $\phi_\gamma \sim -45°$) and $\phi_p = 0°$–$22.5°$ and $225°$–$360°$;

— Clover4 ($\theta_\gamma \sim 145°$, $\phi_\gamma \sim -145°$) and $\phi_p = 0°$–$112.5°$ and $315°$–$360°$.

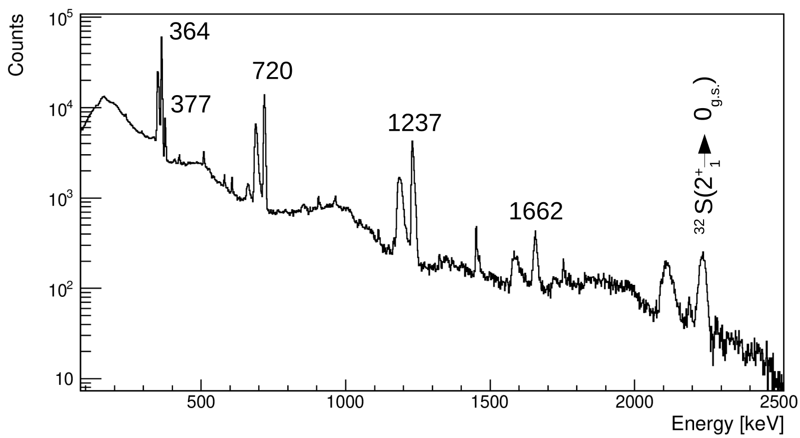

Fig. 3. γ-ray deexcitation spectrum associated with Coulomb excitation of ^{45}Sc, for selected particle-gamma angles, that are listed in the text. Doppler corrected for the projectile ions detected in APPPC. Peaks are marked with their energy in keV.

The Coulomb-excited states populated in the present measurement and the preliminary level scheme of ^{45}Sc are shown in Fig. 4. Further, common analysis of both experimental data sets (from the Heavy Ion Laboratory, University of Warsaw and from the Inter-University Accelerator Centre, New Delhi) using the Coulomb-excitation analysis code — GOSIA, aims to disantangle contributions from the $B(\mathrm{E3}; 7/2^- \to 3/2^+)$ and $B(\mathrm{E3}; 7/2^- \to 5/2^+)$ transition probabilities, and to determine the electromagnetic properties for all Coulomb-excited states in ^{45}Sc isotope.

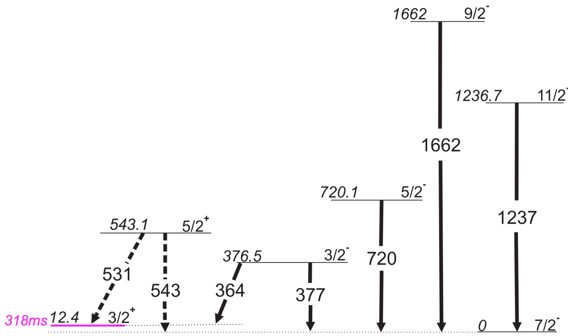

Fig. 4. Preliminary level scheme of ^{45}Sc depicting γ-ray transitions observed in the present Coulomb excitation experiment. The 531 and 543 keV transitions (dashed line) were observed in the HIL UW experiment. Energies are given in keV.

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