EVIDENCE OF ROTATIONAL BEHAVIOUR IN ^{120}Te ISOTOPE*

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A multi-step Coulomb excitation experiment was performed to study the structure of stable ^{120}Te nuclei using a ^{32}S beam from the HIL cyclotron U-200P. The ground-state band up to the 4^+ state was populated. In addition, the excitation of the 2^+_2 and 0^+_2 states was also observed. Magnitudes and relative signs of the transitional matrix elements between the low-lying states in ^{120}Te were determined using the least-squares search code GOSIA. The diagonal matrix elements of the first 2^+ and 4^+ states were extracted.

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1. Introduction

Understanding the evolution of nuclear shell structure as a function of N/Z is one of the main topics in current nuclear structure studies. The Te nuclei, with 52 protons, lie in the transitional region between the spherical nuclei and the deformed Xe and Ba nuclei. Situated near the well-known magic number $Z = 50$, they are good candidates to study the evolving shell structure and interplay of single particle and collective degrees of freedom. At low spin, Te nuclei are considered to be one of the best examples of quadrupole vibrators. This interpretation comes from the energies of the first

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excited 2^+ and 4^+ states which reveal a vibrational pattern almost throughout the isotopic chain, except in the vicinity of $A = 134$. The $B(\mathrm{E2}\uparrow)$ values for the $2^+ \to 0^+$ transitions are predicted to follow a parabolic behaviour around the neutron mid-shell, reaching their maximum at ^{118}Te [1]. This observation is quite in contrast to the measured quadrupole moments Q_2^+ for the doubly-even Te isotopes [2, 3]. These measurements show that the so-called vibrational even–even nuclei have sizable static electric quadrupole moments, which requires a considerable revision of the traditional picture of treating these states as simple one-phonon harmonic surface vibrations, which implies vanishing quadrupole moments.

In our previous Coulomb excitation experiment performed at IUAC, New Delhi [4], we used a ^{58}Ni beam of 175 MeV energy to excite ^{120,122,124}Te isotopes. The scattered particles were detected at forward angles ($15° < \theta_{\mathrm{lab}} < 45°$). The $B(\mathrm{E2};\, 2^+ \to 0^+)$ value in ^{120}Te was re-measured with a much higher precision to allow a comparison with the predictions of the large-scale shell model (LSSM) calculations. In addition, the nuclear structure of ^{120,122,124}Te was also investigated by measuring the absolute $B(\mathrm{E2}\uparrow)$ values to higher-lying states. All experimental findings for ^{120,122,124}Te, including the excitation of higher excited states, agree best with an asymmetric rotor behaviour. To cite an example, the experimental $B(\mathrm{E2};\, 4^+ \to 2^+)/B(\mathrm{E2};\, 2^+ \to 0^+)$ ratio never reaches the vibrational limit ~ 2. Also the $B(\mathrm{E2};\, 2^+_2 \to 2^+)/B(\mathrm{E2};\, 2^+_2 \to 0^+)$ ratio was two orders of magnitude larger than that in the axially symmetric rotor model.

The most sensitive probe to characterize a nuclear excitation is via a measurement of quadrupole moments. Therefore, to further investigate the second-order effects in Coulomb excitation (*i.e.* diagonal matrix elements) and to find an experimental proof of the deformation in ^{120}Te, the present Coulomb excitation experiment was performed at the Heavy Ion Laboratory (HIL), Warszawa, where particle detectors are in the backward direction providing a higher sensitivity to the hitherto unknown quadrupole moments and enabling their more precise measurement.

2. Experimental details

The measurement was carried out using a highly-enriched ^{120}Te target (thickness ~ 0.150 mg/cm^2) and a ^{32}S beam of 90 MeV energy from the U-200P cyclotron at HIL, Warszawa. To ensure a pure electromagnetic interaction, the beam energy was chosen to satisfy Cline's safe energy criterion [5].

The γ rays emitted by the ^{120}Te recoils after Coulomb excitation were detected by the EAGLE array [7] consisting of 15 HPGe detectors of 70% efficiency relative to a 3×3 inch NaI detector (at 1332 keV) and equipped with anti-Compton BGO shields. A compact Coulex chamber [8], equipped with 48 PIN diodes of 0.5×0.5 cm^2 active area, was used for the detection of back-scattered ^{32}S ions. The PIN diodes covered an angular range from $123^\circ \leq \vartheta_{\rm lab} \leq 168^\circ$ (or equivalently $136^\circ \leq \vartheta_{\rm cm} \leq 171^\circ$), which enhanced the probability of multi-step excitation. The data was collected in a particle–γ coincidence mode to uniquely ascribe the observed γ rays to the collision kinematics and later allow us to perform a precise Doppler correction of the measured γ rays.

Multi-step Coulomb excitation of ^{120}Te was observed up to the 4^+ state in the ground-state band. Along with that, the second 0^+ and the second 2^+ states were also populated. The partial level scheme of ^{120}Te is shown in Fig. 1. Time-coincident particle–γ data was collected within a 200 ns window. The HIL cyclotron worked at RF of 14.4 MHz *i.e.* delivered the pulsed beam with a 70 ns repetition time.

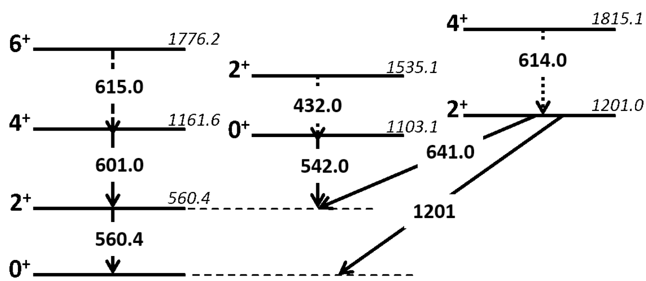

Fig. 1. Partial level scheme of ^{120}Te. The solid lines represent the transitions observed in the present experiment.

3. Coulomb excitation analysis

The offline data analysis was performed using the ROOT-based GO4 analysis software. The data analysis required determination of scattering angles in order to perform the Doppler correction on an event-by-event basis. The precise information about the particle scattering angles (both ϑ and φ) could be obtained from the geometry of the PIN diodes. The particle–γ time coincidence spectra were used to subtract the random background events from the prompt spectra. The width of the time gate was 40 ns. The background-subtracted Doppler-corrected spectrum for ^{120}Te is shown in Fig. 2.

The Coulomb excitation least-squares search code GOSIA [6] was used to determine the transitional and diagonal E2 matrix elements. The code fits a set of reduced matrix elements to reproduce the measured γ-ray yields taking also into account known spectroscopic data related to electromagnetic

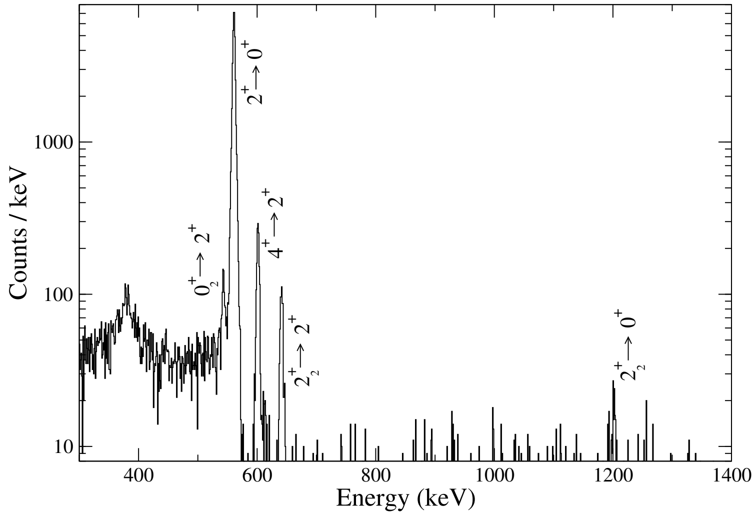

Fig. 2. Background-subtracted Doppler-shift-corrected γ-ray spectrum summed over all EAGLE detectors for the ^{32}S+^{120}Te system at 90 MeV.

matrix elements such as branching ratios, E2/M1 mixing ratios, as well as previously measured matrix elements. The experimental data on lifetimes of several low-lying states, namely 2_1^+, 4_1^+, 6_1^+, 2_2^+, 2_3^+ and 4_2^+, was taken from a recent measurement performed via DSAM technique [9]. The calculated γ-ray yields were corrected for internal electron conversion of electromagnetic transitions and relative efficiency of the γ-ray detectors. Fifteen experimental γ-ray yields were integrated over the particle scattering angles and incident energy range calculated taking into account the energy losses in the target thickness. The best solution corresponds to the smallest overall χ^2 value. To be sure that the fit appropriately converges, it is best to have a number of fitted data points higher than the number of free parameters. Hence, during the analysis, it was decided to sub-divide the experimental data into different angular ranges for the projectile scattering angle, making it possible to disentangle contributions from various excitation paths. The two considered ranges of the projectile scattering angle were $123^\circ < \vartheta_{\mathrm{lab}} < 140^\circ$ and $140^\circ < \vartheta_{\mathrm{lab}} < 168^\circ$.

In the previous measurement [4] at New Delhi, the projectile (^{58}Ni) and target (^{120,122,124}Te) scattering could not be distinguished in the particle detector, but the particle position measurement allowed for a precise Doppler correction of the measured γ rays. Ni projectiles and Te recoils belonged to different scattering regions: $22.2^\circ \leq \vartheta_{\mathrm{cm}} \leq 66.7^\circ$ (^{58}Ni detected in the particle detector) and $90^\circ \leq \vartheta_{\mathrm{cm}} \leq 140^\circ$ (^{120}Te detected in the particle detector). For the close-collision data, where ^{120}Te is detected in the particle detector, the ground state band was populated up to 6^+ spin. To gain more sensitivity to the diagonal E2 matrix element for the first 2^+ state, the experimental data from the close collisions was included as an additional experimental set in GOSIA calculations. The uncertainty of the experimental yield for $6^+ \to 4^+$ transition was about $\sim 5\%$. The precision of the lifetimes of 6^+ and 4^+ states was $\sim 4\%$ and $\sim 6\%$ respectively.

4. Results

The resulting transitional and diagonal E2 matrix elements, deduced B(E2) values and spectroscopic quadrupole moments are presented in Tables I and II. These values are also compared with the results obtained using the Davydov–Fillipov model [10] assuming $\beta = 0.18$ and $\gamma = 27°$, as well as with the predictions of the Interacting Boson Model 2. The details of the IBM-2 calculations can be found elsewhere [4]. The measured value of $Q_{\rm s}(2^+) = -0.41(3)$ eb provides an experimental proof of the prolate shape of the ^{120}Te nucleus in the 2^+_1 state.

TABLE I

The set of matrix elements (in eb) and B(E2) values (in e^2b^2) obtained using the GOSIA code. The present experimental values are compared with the calculations using the Davydov–Fillipov model and IBM-2.

Transition	Experiment		Theory	
$I_{\rm i} \to I_{\rm f}$	$\langle I_{\rm f}\|\|E2\|\|I_{\rm i}\rangle$ [eb]	$B(\mathrm{E2}{\downarrow})$ [e^2b^2]	D.–F. model	IBM-2
$2^+_1 \to 0^+$	0.778 ± 0.014	0.121 ± 0.004	0.120	0.135
$4^+_1 \to 2^+_1$	1.342 ± 0.019	0.200 ± 0.006	0.168	0.205
$2^+_2 \to 2^+_1$	0.955 ± 0.020	0.183 ± 0.009	0.142	0.212
$2^+_2 \to 0^+$	0.161 ± 0.011	0.0052 ± 0.0008	0.002	0.002

TABLE II

The set of E2 diagonal matrix elements and corresponding spectroscopic quadrupole moments $Q_{\rm s}$ (in eb) obtained using the GOSIA code. The present experimental values are compared with the results of the Davydov–Fillipov model calculations.

State	Present		D.–F. model
$I_{\rm i}$	$\langle I_{\rm i}\|\|E2\|\|I_{\rm i}\rangle$ [eb]	$Q_{\rm s}$ [eb]	($\beta = 0.18,\ \gamma = 27°$)
2^+_1	-0.55 ± 0.04	-0.41 ± 0.03	-0.304
4^+_1	-1.02 ± 0.25	-0.77 ± 0.19	-0.159

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