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DEFORMATION IN ^{120}Te DESCRIBED EXPERIMENTALLY BY QUADRUPOLE INVARIANTS*

M. Saxena[a], P. Napiorkowski[a], L. Próchniak[a], R. Kumar[b]
A. Stolarz[a], K. Wrzosek-Lipska[a], T. Abraham[a], S. Dutt[c]
M. Kicińska-Habior[d], M. Kisieliński[a], M. Komorowska[a]
M. Kowalczyk[a], M. Matejska-Minda[a,e], M. Palacz[a], W. Piątek[a]
J. Srebrny[a], A. Tucholski[a] H.-J. Wollersheim[f]

[a]Heavy Ion Laboratory, University of Warsaw
Pasteura 5a, 02-093 Warszawa, Poland
[b]GDA Group, Inter University Accelerator Centre, New Delhi-110 067, India
[c]Department of Physics, Aligarh Muslim University, Aligarh-202 002, India
[d]Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland
[e]Institute of Nuclear Physics Polish Academy of Sciences, 31-342 Kraków, Poland
[f]Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

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The last stable tellurium nucleus on the neutron-deficient side, ^{120}Te, was Coulomb excited using two different projectiles. The low-lying collective states were populated in a multi-step Coulomb excitation process. Magnitudes and relative signs of the reduced E2 matrix elements were determined using the GOSIA code. The resulting set of E2 matrix elements was analysed using the quadrupole sum rules approach to determine the quadrupole deformation parameters for the 0_1^+ and 2_1^+ states.

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1. Introduction

The pattern of low-energy levels in the mid-shell even-A Te isotopes suggests that these nuclei can be considered as a good example of harmonic vibrators. However, a detailed analysis of the electromagnetic properties of these nuclei, *e.g.* large value of a quadrupole moment of the 2_1^+ states for even–even Te isotopes with $A > 120$, do not confirm such simple description. In a multi-step Coulomb excitation, low-lying nuclear states are populated and a set of electromagnetic matrix elements can be obtained to describe the

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low-energy nuclear structure of a nucleus. From the set of matrix elements, we can determine the expectation values of the intrinsic-frame E2 moments, which are directly related to quadrupole deformation and degree of triaxiality for the ground and excited states.

In the present paper, we provide details of Coulomb excitation studies concerning the low-energy electromagnetic structure of ^{120}Te nucleus. The deformation parameters for the ground state and excited 2^+ state were extracted from the experimental E2 transitions using the rotational invariants method.

2. Experiments

Two experiments were performed to study the ^{120}Te nucleus. Two projectiles, provided by the U-200P cyclotron facility at the Heavy Ion Laboratory (HIL), University of Warsaw and 14UD Tandem Accelerator at the Inter University Accelerator Centre (IUAC), New Delhi, ^{32}S and ^{58}Ni were accelerated up to 90 MeV and 175 MeV, respectively, and bombarded on a highly enriched ^{120}Te target. In both experiments, the energy of the beam was lower than the Cline's "safe" energy criterion fulfilling that the distance of closest approach for a head-on collision should exceed $[1.25(A_{\mathrm{P}}^{1/3}+A_{\mathrm{T}}^{1/3})+5]$ fm [1]. This ensured that the excitation process is dominated by the well-known electromagnetic interaction and the contribution from the nuclear force is insignificant. The EAGLE array at HIL, Warsaw [2], comprising of 15 anti-Compton suppressed germanium detectors was used to detect de-exciting γ-rays from the Te recoils. A dedicated scattering chamber [3], with 48 Pin diodes was used to detect the scattered projectile ions. The particle detectors were placed at backward angles covering a range from 110 to 167 degrees in the laboratory frame. For the experiment performed at IUAC, New Delhi, an annular parallel plate avalanche counter was placed at forward angles with respect to the beam direction to detect both the scattered projectiles and ejectiles. Four clover detectors were positioned at ± 145 degrees for measuring the γ-ray emitted by the Coulomb excited target nuclei [4]. In both measurements, the data was collected in a coincidence requirement between the γ-ray and the scattered particle.

The set of E2 matrix elements was obtained to optimally reproduce the measured γ-ray intensities following the χ^2 minimization algorithm defined in the GOSIA code [5]. Supplementary spectroscopic information, including the lifetimes [6], branching ratio and mixing ratio [7], was used as additional constraints in the multi-dimensional fit. In total, 31 experimental data points were fitted to extract three diagonal and six transitional E2 matrix elements including their relative signs. The E2 diagonal matrix elements for the low-lying 2^+ and 4^+ were precisely determined for the first time. The diagonal matrix elements are related directly to the spectroscopic quadrupole moments (Q_{s}). The obtained large non-zero values of quadrupole moments cannot be interpreted within a simple vibrational model, which is suggested for this nucleus and based on level-energy pattern of the low-lying states. The intrinsic deformation parameters can be extracted from the set of electromagnetic matrix elements by evaluating rotationally invariant scalar products of the electric quadrupole operator.

3. Sum rules method

The set of matrix elements was used to obtain a model-independent description of the nuclear shape in terms of quadrupole deformation parameters [1, 8]. This can be done as the electric quadrupole operator, $E(\lambda = 2, \mu)$, is a spherical tensor and zero-coupled products of such operators can be constructed that are rotationally invariant. The zero-coupled products of the E2 operators can be related to the deformation parameters in the intrinsic frame of the nucleus, Q and δ. Here, Q represents the overall deformation of a given state and δ is the triaxiality parameter, for a detailed discussion see [9]. The Q and δ quantities play an analogous role to Bohr collective shape variables $\langle\beta\rangle$ and $\langle\gamma\rangle$, respectively. The simplest zero-coupled product of the E2 operator can be written as

$$\frac{1}{\sqrt{5}}\left\langle Q^2\right\rangle = \langle i||[\mathrm{E2}\times\mathrm{E2}]_0||i\rangle\,, \tag{1}$$

$$-\sqrt{\frac{2}{35}}\left\langle Q^3\cos(3\delta)\right\rangle = \langle i||[\mathrm{E2}\times\mathrm{E2}]_2\times\mathrm{E2}_0||i\rangle\,. \tag{2}$$

In the laboratory frame, the expectation values of the lowest order rotational invariants, $\langle Q^2\rangle$ and $\langle Q^3\cos(3\delta)\rangle$ can be determined by expanding r.h.s. of Eqs. (1) and (2) over all possible intermediate states, which can be reached via a single E2 transition

$$\left\langle Q^2\right\rangle = \frac{1}{2I_i+1}\sum_t(-1)^{I_t-I_i}\langle i||\mathrm{E2}||t\rangle\,\langle t||\mathrm{E2}||i\rangle\,, \tag{3}$$

$$\begin{aligned}\left\langle Q^3\cos(3\delta)\right\rangle &= -\frac{1}{2I_i+1}\sqrt{\frac{35}{2}}\\ &\quad\times\sum_{s,t}\langle i||\mathrm{E2}||s\rangle\,\langle s||\mathrm{E2}||t\rangle\,\langle t||\mathrm{E2}||i\rangle\left\{\begin{array}{ccc}2&2&2\\ I_i&I_t&I_s\end{array}\right\}.\end{aligned} \tag{4}$$

The negative sign in Eq. (4) is for integral spin of the state. The deformation parameters of a state can be determined in a nuclear model-independent way by summing over all possible closed loops of E2 matrix elements related to a specific state. The lowest order rotational invariant, *i.e.* an expectation value of the square of the quadrupole deformation parameter, $\langle Q^2 \rangle$, is proportional to the sum of the squared matrix elements containing all closed $\mathrm{E2} \times \mathrm{E2}$ loops. The next higher order invariant, $\langle Q^3 \cos(3\delta) \rangle$, is constructed from sums of $\mathrm{E2} \times \mathrm{E2} \times \mathrm{E2}$ triple products of the matrix elements and the information on the relative signs of E2 matrix elements is also needed. The $\langle Q^2 \rangle$ value may be underestimated due to the limited knowledge of complete set of 2^+ states (see Eq. (3)). However, for $\langle Q^3 \cos(3\delta) \rangle$ invariant, the value may be increased or decreased depending on the relative signs of the matrix elements.

The obtained experimental results allowed us to analyse the rotational invariants for the lowest 0_1^+ and 2_1^+ states in ^{120}Te nucleus. The level scheme used in the analysis is shown in Fig. 1. The determined $\langle Q^2 \rangle$ and $\langle Q^3 \cos(3\delta) \rangle$ values are presented in Figs. 2 and 3. These experimental values are also compared with the theoretical results obtained within the General Bohr Hamiltonian (GBH) approach based on the microscopic mean-field theory. We employed two parametrizations of the effective nucleon–nucleon interaction, namely the well-known SLy4 variant and the more recently proposed UNEDF0 [11]. The calculations were performed along the lines presented in [12]. It should be mentioned that within used theory the invariants are calculated directly, it is as the left-hand side of Eqs. (3) and (4).

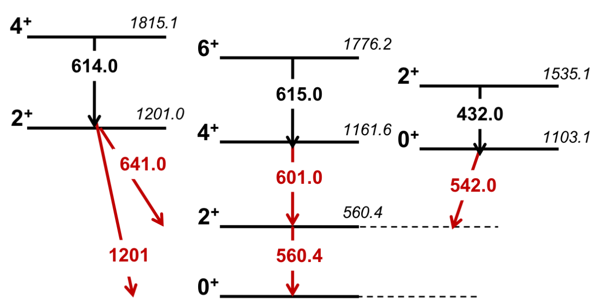

Fig. 1. The partial level scheme showing the low-lying energy levels in ^{120}Te nucleus. The transitions observed in the ^{32}S experiment are indicated in grey/red. The level energies are in keV.

The experimental overall deformation, $\langle Q^2 \rangle$, for the 0^+ ground state was determined by considering all coupling between the 0_1^+ state and higher lying 2^+ states, as depicted in the level scheme (see Fig. 1). The contribution from the excited 2_3^+ state, which was not directly observed in the present experiment, was estimated using the lifetime [6] and branching ratio data [7]. While determining the $\langle Q^2 \rangle$ invariant for excited 2_1^+ state, more rich experimental information is needed. In addition to the excited 2^+ states, we must also include in the summation matrix elements involving the E2 transitions to the excited 4^+ states. The obtained experimental overall deformation for both 0_1^+ and 2_1^+ states is similar as shown in Fig. 2. For the 0^+ ground state, the experimental value for $\langle Q^2 \rangle$ is in fair agreement with the theoretical predictions. The $\langle Q^2 \rangle$ value seems to be slightly underestimated under the predictions estimated by GBH using UNEDF0 Skyrme interaction. However, using the SLy4 Skyrme, we obtained larger value for the overall deformation parameter.

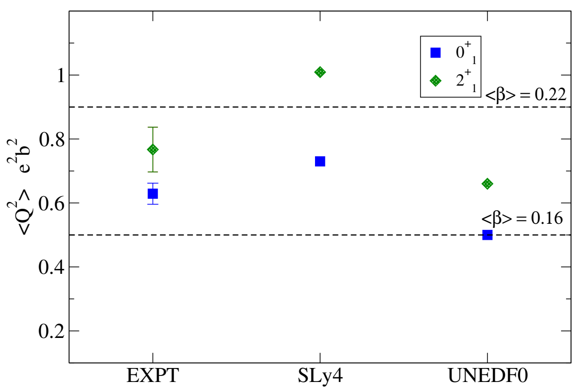

Fig. 2. Experimental and theoretical values for the expectation of quadrupole invariant $\langle Q^2 \rangle$, for the 0_1^+ and 2_1^+ states in ^{120}Te. The obtained values of quadrupole invariants can be related, under certain assumptions, to the Bohr $\langle \beta \rangle$ parameter, following the prescription given in [10]. The dashed lines show two different values for the $\langle \beta \rangle$ parameter.

To obtain the triaxiality parameter, $\langle Q^3 \cos(3\delta) \rangle$, more experimental information is needed than in the case of the $\langle Q^2 \rangle$ value. As can be seen from Eq. (4), the triaxiality parameter for low-lying 0^+ states can be determined from summation of E2 $\times$ E2 $\times$ E2 triple products. To calculate $\langle Q^3 \cos(3\delta) \rangle$ invariant for the 0^+ ground state, the contributions from the transitional matrix elements that couple excited 2^+ states via a single E2 transition need to be taken into account. In addition, diagonal E2 matrix elements of all excited 2^+ states are also required. Due to limited experimental information concerning the higher-lying levels, we could only estimate a range of possible values of $\langle Q^3 \cos(3\delta) \rangle$ invariant for the 0^+ ground state, as shown in Fig. 3. The contributions related with the couplings of the 2_3^+ state were estimated from the lifetime and branching ratio [6, 7]. The influence of different signs of the inter-band matrix elements *i.e.* $\langle 2_3^+ || \mathrm{E2} || 0_1^+ \rangle$ and $\langle 2_3^+ || \mathrm{E2} || 2_2^+ \rangle$, was

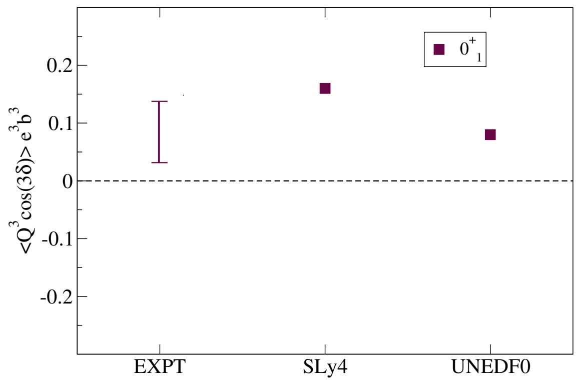

Fig. 3. Experimental limits and theoretical values for the expectation of quadrupole invariant $\langle Q^3 \cos(3\delta)\rangle$ for for the 0_1^+ state in ^{120}Te. The dashed line corresponds to $\langle\gamma\rangle$ parameter equal to 30°, following the prescription given in [10].

also investigated. The magnitude of the unknown diagonal E2 matrix element for the 2_3^+ state was assumed following the rotational model. Both positive and negative values of $Q_{\rm s}(2_3^+)$ were considered. All afore-mentioned contributions were incorporated to estimate the limits for the $\langle Q^3 \cos(3\delta)\rangle$ invariant for the 0_1^+ state. The limits correspond to a range of $\langle\gamma\rangle$ parameter between 25° and 29°, following prescription in [10]. The obtained range for $\langle Q^3 \cos(3\delta)\rangle$ value is consistent with the theoretically determined invariants and is close to 0.

4. Conclusion

The large value of diagonal matrix elements for 2_1^+ and 4_1^+ states cannot be explained within a simple vibrational model which is usually invoked when taking into account the energy spectrum. Moreover, expected values of the lowest quadrupole invariant operator, $\langle Q^2\rangle$, in the 0_1^+ and 2_1^+ state obtained in a model-independent way by the non-energy weighted quadrupole sum rules technique suggest quasi-rotational character of the ground state band in ^{120}Te. Our results show that simple schematic models (vibrational or rotational) are plainly insufficient to describe collective dynamics of the ^{120}Te nucleus quantitatively. More general theoretical approach, *i.e.* the GBH model, which treats both vibrational and rotational degrees of freedom on equal footing, makes it possible to reproduce almost harmonic energies and non-zero quadrupole moments simultaneously.

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