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Full Paper

B(E2) values of Te isotopes with even N (68-74) by means of interacting boson model-1

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Abstract: The electric reduced transition probabilities B(E2)↓ of even-neutron-rich $^{120\text{-}126}$Te nuclei by means of interacting boson model-1 (IBM-1) are calculated. The $R_{4/2}$ values of the first 4^+ and 2^+ levels are also calculated and the U(5) symmetry for these nuclei is indicated. The transition rate $R = B(E2: L^+ \rightarrow (L\text{-}2)^+)/ B(E2: 2^+ \rightarrow 0^+)$ of a few low-lying quadrupole collective states is studied systematically and compared with the experimental data. The electric reduced transition probabilities of even $^{120\text{-}126}$Te nuclei of gamma transition states of $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ are studied and compared with the experimental values. In addition, the systematic B(E2) values, intrinsic quadrupole moments and deformation parameters of even neutrons of *N*= 68-74 in Te isotopes are also studied. All the computed values from the present study are in good agreement with the experimental data. The IBM-1 formula for the reduced transition probabilities B(E2) is analytically deduced in U(5) limit for a few ground-state transitions in even $^{120\text{-}126}$Te isotopes.

Keywords: reduced transition probabilities, Te isotopes, quadrupole moments, deformation parameter, yrast state band

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INTRODUCTION

The interacting boson model-1 (IBM-1) was developed by Iachello and Arima [1, 2]. This model is essential for explaining the collective nuclear structure and successfully predicts the low-lying states. The IBM-1 effectively describes the electromagnetic transition rates in medium-mass nuclei. Only the s-boson pair and d-boson pair with angular momentum L =0 and L= 2 respectively are taken into account in the first approximation. The limiting symmetries U(5), SU(3) and O(6) with an inherent group structure are associated with this model [1, 3].

In recent years extensive experimental as well as theoretical studies were carried out to explore the even-even tellurium isotopes Te (Z=52) with special focus on the experimental data via collective models. It is an attractive challenge to search for collective properties because these exist near the magic number 50, which is found in single closed-shell Sn nuclei. Yrast states up to $I^{\pi}= 8^+$ in Z= 52 isotones have been found as $\pi h^2_{11/2}$ configurations for Z=50 closed shells. There are many experimental and theoretical studies concerning the low-lying collective quadrupole *E2* excitations that occur in even-even nuclei Z=52 [4-7]. In the framework of semi-microscopic model, the B(E2) values and electric quadrupole moments of $^{120\text{-}128}$Te isotopes have been studied [8]. The two-proton core coupling model [9], dynamic deformation model [10] and interacting boson model-2 have also been used for the same purpose [11-13].

The IBM-1 model has been employed theoretically to study the intruder configuration and configuration mixing around the shell closure Z=50. The empirical spectroscopic study within the configuration mixing calculation was conducted in IBM [14, 15] and IBM-associated models such as the configuration mixing model in strong connection with shell model [16, 17], the conventional collective Hamiltonian approach [18, 19] and the microscopic energy-density function [20]. The evolution properties of even-even $^{100\text{-}110}$Pd [21] and electromagnetic reduced transition probabilities of even-even $^{104\text{-}112}$Cd [22], $^{102\text{-}106}$Pd [23], $^{108\text{-}112}$Pd [24] and $^{100\text{-}102}$Ru [25] have been studied very recently.

The reduced E2 probability B(E2↑) merely depends on the magnitude of intrinsic quadrupole moment of the nucleus, which depends on the deformation [26]. The aim of the present work is to do a microscopic study of the even-even Te isotopes within the IBM in order to obtain a comprehensive view of these isotopes in a rather simple way. The transition rates of yrast state band up to $8^+ \rightarrow 6^+$ level are calculated by using the *E2* transition strengths, deformation parameter and intrinsic quadrupole moment. With more data accumulated over the past 12 years, it is interesting to re-examine the situation. For this purpose, we do an extensive analysis of the low-lying structure of even $^{120\text{-}126}$Te isotopes by IBM-1. We particularly focus our attention to the analytically deduced U(5) symmetry for a yrast state transition in even $^{120\text{-}126}$Te isotopes.

METHODS

Reduced Transition Probabilities B(E2)

In the simplest version of the IBM, it is assumed that the low-lying collective states in medium and heavy even-even nuclei away from closed shells are dominated by excitation of the valence protons and the valence neutrons only (i.e. particles outside the major closed shells at 2, 8, 20, 28, 50, 82 and 126), while the closed shell core is inert. Furthermore, it is assumed that the particle configurations are coupled together, forming pairs of angular momentum 0 and 2. These proton (neutron) pairs are treated as bosons. Proton (neutron) bosons with angular momentum L = 0 are denoted by s_π (s_ν) and are called s-bosons, while proton (neutron) bosons with angular momentum L = 2 are denoted by d_π(d_ν) and are called d-bosons. The underlying structure of the six dimensional unitary groups U(6) of the model leads to a simple Hamiltonian, capable of describing the three specific types of collective structure with classical geometrical analogs, namely vibrational

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U(5), rotational SU(3) and γ-unstable O(6). Hamiltonian H can be written explicitly in terms of boson creation ($s^\dagger, d^\dagger$) and annihilation ($\tilde{s}, \tilde{d}$) operators [2], such that

$$H = \varepsilon_s[(s]^\dagger . \tilde{s}) + \varepsilon_d(d^\dagger . \tilde{d}) + \sum_{L=0,2,4} \frac{1}{2}(2L+1)^{\frac{1}{2}} C_L \left[(d^\dagger \times d^\dagger)^{(L)} \times (\tilde{d} \times \tilde{d})^{(L)}\right]^{(0)}$$
$$+\frac{1}{\sqrt{2}} v_2\left[(d^\dagger \times d^\dagger)^{(2)} \times (\tilde{d} \times [\tilde{s})]^{(2)} + (d^\dagger \times [s^\dagger)]^{(2)} \times (\tilde{d} \times \tilde{d})^{(2)}\right]^{(0)}$$
$$+\frac{1}{2} u_0\left[(s^\dagger \times s^\dagger)^{(0)} \times (\tilde{s} \times [\tilde{s})]^{(0)}\right]^{(0)} + u_2\left[(d^\dagger \times s]^\dagger)^{(2)} \times [(\tilde{d} \times \tilde{s})^{(2)}\right]^{(0)}, \quad (1)$$

where it can be written in general form as [2]:

$$H = \varepsilon \hat{n}_d + a_0 \hat{p}.\hat{p} + a_1 \hat{L}.\hat{L} + a_2 \hat{Q}.\hat{Q} + a_3 \hat{T}_3.\hat{T}_3 + a_4 \hat{T}_4.\hat{T}_4 , \quad (2)$$

where $\hat{n}_d = (d^\dagger.\tilde{d})$, the total number of d_{boson} operator; $\hat{p} = \frac{1}{2}\left[(\tilde{d}.\tilde{d}) - (\tilde{s}.\tilde{s})\right]$, the pairing operator; $\hat{L} = \sqrt{10}(d^\dagger \times \tilde{d})^{(1)}$, the angular momentum operator; $\hat{T}_r = (d^\dagger \times \tilde{d})^{(r)}$, the octupole and hexadecapole operator; $\varepsilon = \varepsilon_d - \varepsilon_s$, the boson energy; and $\hat{Q} = (d^\dagger \times \tilde{s} + s^\dagger \times \tilde{d})^{(2)} + \chi(d^\dagger \times \tilde{d})^{(2)}$ (χ=CHQ), the quadrupole operator. The parameters a_0, a_1, a_2, a_3 and a_4 designate the strength of the pairing, angular momentum, quadrupole, octupole and hexadecapole interactions respectively between the bosons.

Even-even nuclei of low-lying levels (L_i =2, 4, 6, 8…….) usually decay by *E2* transition to lower-lying yrast level with $L_f = L_i$-2. The reduced transition probabilities in IBM-1 are given for anharmonic vibration limit *U(5)* [27] by:

$$B(E2;\ L+2 \rightarrow L)\downarrow = \frac{1}{4}\alpha_2{}^2(L+2)(2N-L) = \frac{1}{4}\frac{(L+2)(2N-L)}{N}B(E2;2 \rightarrow 0) \quad (3)$$

where *L* is the angular momentum and *N* is the boson number. The boson number is half of the valence nucleons (proton and neutrons). For every isotope, the value of parameter α_2^2 (square of effective charge) can be calculated by using the experimental value B(E2) of transition $2^+ \rightarrow 0^+$, and then the α_2^2 value is employed to compute the transition $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$.

Quadrupole Moments and Deformation Parameters

The intrinsic quadrupole moments (Q_0) of the nuclei can be derived as [28]:

$$Q_0 = \left[\frac{16\pi}{5}\frac{B(E2)\uparrow}{e^2}\right]^{1/2} \quad (4)$$

The upward electromagnetic quadrupole transition probability B(E2)↑ is related by [29]:

$$B(E2;\ L_i \rightarrow L_f)\downarrow = B(E2,\ L_f \rightarrow L_i)\uparrow * g \quad (5)$$

with $g = (2L_f+1)(2L_i+1)^{-1}$ (6)

The relationship between the value of B(E2) in unit of e^2b^2 and B(E2) in Weisskopf unit (W.u.) is [30]:

$$B(E2)\ e^2b^2 = 5.94 * 10^{-6} * A^{4/3} * B(E2)\ W.u. \quad (7)$$

where *e* denotes the charge of electron, *b* (barn) is a unit of area and A is the mass number of nucleus.

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The probability B(E2)↑ of transition $0_1^+ \rightarrow 2_1^+$ is related to the quadrupole deformation parameter β [31] of nucleus shape in equilibrium as:

$$B[E2;0^+ \rightarrow 2^+]\uparrow \; = [(3/4\pi)eZ R_0^2]^2\beta^2 \qquad (8)$$

and β can be calculated as [31]:

$$\beta \; = [B(E2)\uparrow]^{1/2} [3ZeR_0^2/4\pi]^{-1} \qquad (9)$$

where Z is the atomic number and R_0 is the average radius of nucleus given by

$$R_0^2 = 0.0144\, A^{2/3}\, b \qquad (10)$$

RESULTS AND DISCUSSION

Reduced Transition Probabilities

The reduced transition probabilities are important for the structural information regarding the nucleus. The boson number is counted as the number of collective pairs of valence nucleons and it represents the pair of valence nucleons. We have calculated the boson number, transition level and downward electric quadrupole reduced transition probabilities B(E2)↓ for the yrast state bands $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ of even-even $^{120\text{-}126}$Te isotopes (Table 1). A correlation exists between the nuclei that show identical spectra and their valence proton numbers *(N_p)* and neutron numbers *(N_n)*. The numbers of valance proton N_p and neutron N_n have a total $N = (N_p + N_n)/2 = n_\pi + n_\nu$ bosons. To find the boson number, the ^{132}Sn doubly-magic nucleus is taken as an inert core. The reduced transition probabilities of $4_1^+ \rightarrow 2_1^+$, $6_1^+ \rightarrow 4_1^+$ and $8_1^+ \rightarrow 6_1^+$ transitions of even-even ^{120,122,124,126}Te isotopes are calculated using known B(E2)↓ experimental data from the $2_1^+ \rightarrow 0_1^+$ transition. The calculated results of B(E2)↓ values are also compared with the previous experimental results [32-35].

Table 1. Reduced transition probabilities B(E2)↓ in even $^{120\text{-}126}$Te isotopes

Nucl.	Boson no. $N_\pi + N_\nu = N$	α_2^2 W.u.	L^+	$E_{exp}(L)$ keV	Transition Level	E_γ keV	$B(E2)_{[32\text{-}35]}$ W.u.	$B(E2)_{IBM\text{-}I}$ W.u.
^{120}Te	1 + 7 = 8	4.62±0.03	2	560.44	$2^+ \rightarrow 0^+$	560.4	31±6	31 ± 6
			4	1161.56	$4^+ \rightarrow 2^+$	601.1		64.61 ± 0.43
			6	1776.23	$6^+ \rightarrow 4^+$	614.6		83.07 ± 5.58
			8	2652.97	$8^+ \rightarrow 6^+$	876.7		92.3 ± 0.62
^{122}Te	1 + 6 = 7	5.27±0.04	2	564.1	$2^+ \rightarrow 0^+$	564.1	36.92±0.25	36.92±.25
			4	1181.2	$4^+ \rightarrow 2^+$	617.2		63.24±0.48
			6	1751.3	$6^+ \rightarrow 4^+$	570.0		79.05±0.60
			8	2669.7	$8^+ \rightarrow 6^+$	918.5	61 ±21	84.32 ±0.64
^{124}Te	1 + 5 = 6	5.18±0.08	2	602.7	$2^+ \rightarrow 0^+$	602.7	31.1±0.5	31.1±0.5
			4	1248.6	$4^+ \rightarrow 2^+$	645.9	44.45±6.6	51.8 ±0.8
			6	1746.9	$6^+ \rightarrow 4^+$	498.4		62.16 ±0.96
			8	2664.4	$8^+ \rightarrow 6^+$	917.4		62.16 ±0.96
^{126}Te	1 + 4 = 5	5.08±0.14	2	666.3	$2^+ \rightarrow 0^+$	666.3	25.4±0.7	25.4±0.7
			4	1361.4	$4^+ \rightarrow 2^+$	695.0	34±16	40.64±1.12
			6	1776.2	$6^+ \rightarrow 4^+$	414.7		45.72±1.26
			8	2765.8	$8^+ \rightarrow 6^+$	989.6		40.64 ±1.12

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Table 2 shows the calculation results of upward electric quadrupole reduced transition probabilities B(E2)↑ of the ground state bands $0_1^+ \rightarrow 2_1^+$, $2_1^+ \rightarrow 4_1^+$, $4_1^+ \rightarrow 6_1^+$ and $6_1^+ \rightarrow 8_1^+$ of even-even $^{120\text{-}126}$Te isotopes. The intrinsic quadrupole moments Q_0 and deformation parameter β were simply calculated from B(E2) values using the restrictive assumption about the rigid shape of a nucleus and were compared to the available values [29]. The calculated results for B(E2)↑, Q_0 and β values were found to be consistent with those given in the literature [31-35].

Table 2. Quadrupole moments (Q_o) and deformation parameters (β) of even $^{120\text{-}126}$Te isotopes

Nucl.	Transition	B(E2)↑[31] e^2b^2	B(E2)↑$_{IBM\text{-}1}$ e^2b^2	β[31]	β_{cal}	Q_o[31] b	$Q_{o(cal)}$ b
^{120}Te	$0^+ \rightarrow 2^+$	0.77(16)	0.54(10)	0.201(21)	0.170(74)	2.77(29)	2.34(96)
^{122}Te	$0^+ \rightarrow 2^+$	0.660(6)	0.662(5)	0.1847(8)	0.1857(61)	2.576(12)	2.58(22)
^{124}Te	$0^+ \rightarrow 2^+$	0.568(6)	0.572(9)	0.1695(9)	0.1808(226)	2.390(13)	2.54(32)
^{126}Te	$0^+ \rightarrow 2^+$	0.475(10)	0.476(13)	0.2534(16)	0.278(46)	2.185(23)	2.19

$R_{4/2}$ Classifications

The dynamical symmetries $U(5)$, $SU(3)$ and $O(6)$ are grouped into classes. Within each class the ratio of energy levels of the first 4^+ and first 2^+, i.e. $E(4_1^+)/E(2_1^+)$ or $R_{4/2}$, can be used to classify the even-even nuclei [36-37]. The yield values of $R_{4/2}$ is equal to 2.00, 2.5 and 3.33 for harmonic vibrator $U(5)$, γ-unstable $O(6)$ and axially symmetric rotor $SU(3)$ respectively. The variation of $E(4_1^+)/E(2_1^+)$ versus even neutron numbers of Te isotopes for the reported experimental values of $U(5)$, $O(6)$ and $SU(3)$ limits [32-35] is shown in Figure 1. We identify $U(5)$ symmetry in even $^{120\text{-}126}$Te isotopes because their $R_{4/2}$ values are ~ 2.00.

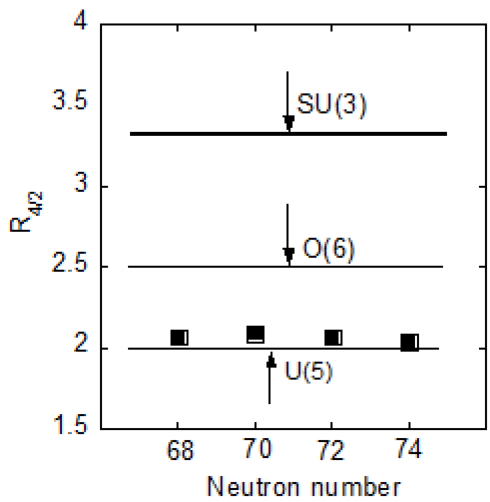

Figure 1. $E(4_1^+)/E(2_1^+)$ or $R_{4/2}$ values as a function of even neutron numbers of $^{120\text{-}126}$Te isotopes (Black squares are from literature [32-35]). $R_{4/2}$ values (2.00, 2.5 and 3.33) are indicated (arrows) for harmonic vibrator $U(5)$, γ-unstable $O(6)$ and axially symmetric rotor $SU(3)$.

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Systematic Reduced Transition Probabilities B(E2)

Using equation (1), the effective charge (α_2) of IBM-1 is determined by normalising the experimental data $B(E2;2_1^+ \to 0_1^+)$ of each isotope. From the known experimental values of transition ($2_1^+ \to 0_1^+$), we calculate the value of parameter α_2^2 for each isotope and use this value to calculate transitions $4^+ \to 2^+$, $6^+ \to 4^+$ and $8^+ \to 6^+$. Values of the fitted parameter α_2^2 with error indicate the square of effective boson charge and are presented in Table 1. Figure 2 shows theoretical and experimental values of B(E2) in W.u., plotted as a function of transition level. Calculated reduced transition probabilities using IBM-1 as a function of transition level of ground-state band are distinctly separated for different numbers of neutrons, and the B(E2) values increase in an approximately linear fashion with the increasing neutron number for any specific transition. The results of the present work are in good agreement within experimental errors [32-35].

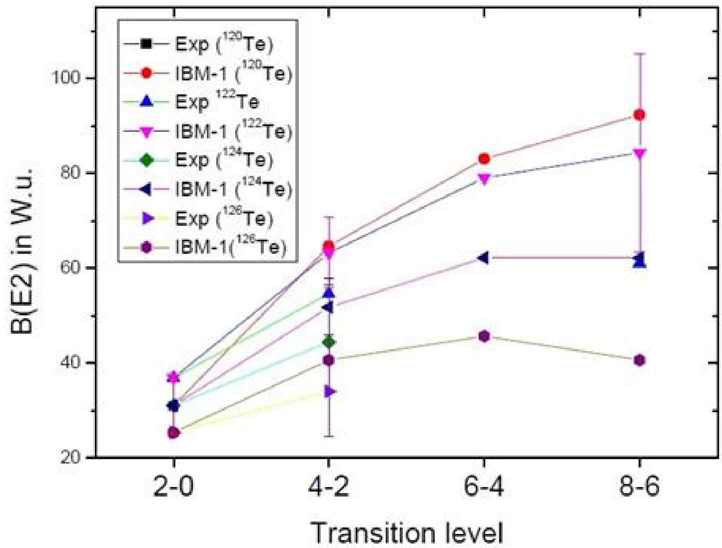

Figure 2. B(E2) values in W.u. as a function of transition of yrast level. Calculated values for B(E2) are compared with available previous experimental values [32-35].

According to the *U(5)* limit, $B(E2;\, 4_1 \to 2_1)/\, B(E2;\, 2_1 \to 0_1) = 2(N\text{-}1)/N < 2$ [27], and these ratios are equal to 1.43±0.23 and 1.34±0.40 for ^{124}Te and ^{126}Te respectively. The 2(*N*-1)/*N* values are equal to 1.75, 1.71, 1.67 and 1.60 for ^{120}Te, ^{122}Te, ^{124}Te and ^{126}Te respectively. Therefore, the present calculations of *U(5)* limit are confirmed by B(E2) ratios as $B(E2;\, 4_1 \to 2_1)/\, B(E2;\, 2_1 \to 0_1) = 2(N\text{-}1)/N < 2$ [27]. A good agreement between the calculated and experimental values indicates that Te isotopes obey *U(5)* limit.

Quadrupole Moments and Deformation Parameter (β)

The quadrupole moment (Q) is an important property for nuclei and is defined as the deviation from the spherical charge distribution inside the nucleus. The intrinsic quadrupole moments Q_0 are calculated using Eq. (2) for even-even $^{120\text{-}126}$Te nuclei and are shown in Figure 3. They are simply calculated from B(E2) values using the restrictive assumption about the rigid shape of a nucleus and are compared with previous values [31] and found to be in good agreement.

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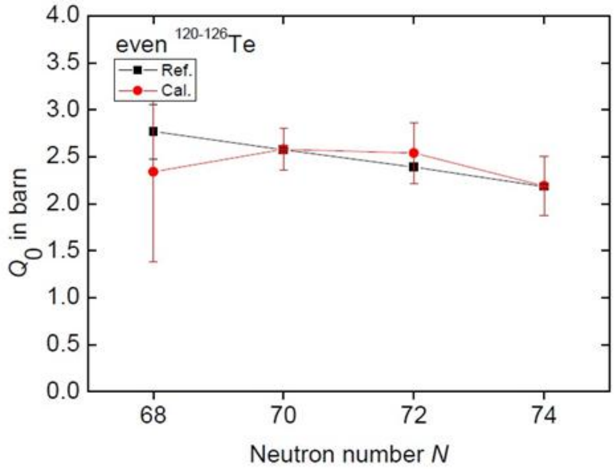

Figure 3. Intrinsic quadrupole moment as a function of even neutron of $^{120-126}$Te isotopes

The deformation parameters (β) of nuclei with proton Z=52 and even neutron N= 68-74 are obtained using Eq. (9) and presented in Table 2 and Figure 4. The calculated deformation parameters using the restrictive assumption about the rigid shape of a nucleus are compared with those given in the literature [31]. From Table 2 and Figure 4, it is noted that the deformation parameter increases with increasing neutron number and the present calculation results are consistent with those from the literature [31].

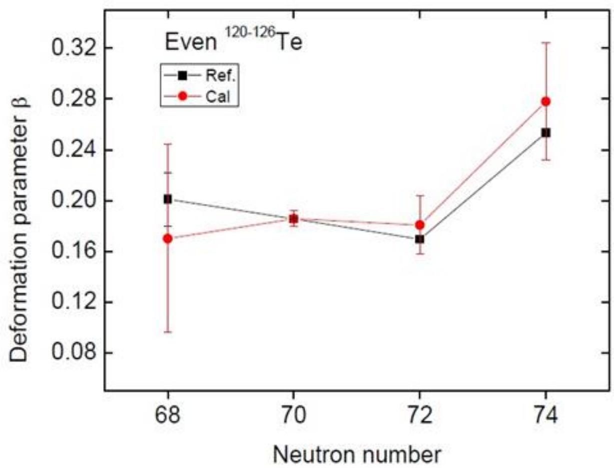

Figure 4. Deformation parameter as a function of even number of neutrons in $^{120-126}$Te isotopes

CONCLUSIONS

Downward electric quadrupole reduced transition probabilities B(E2)↓ for the yrast state bands from $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ of even-even $^{120-126}$Te isotopes by IBM-1 have been reported. Using the restrictive assumption about the rigid shape of the nucleus, the calculated quadrupole moments and deformation parameters are found to be consistent with previous results. The calculated upward electric quadrupole reduced transition probabilities B(E2)↑ from $0_1^+ \rightarrow 2_1^+$ of even-even $^{120-126}$Te isotopes are in good agreement with the adopted values. The analytic IBM-1 calculation of B(E2) values of even-even $^{120-126}$Te has been performed in U(5) character.

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