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Interacting boson model (IBM-2) calculations of selected even-even Te nuclei

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ABSTRACT

In this study, we have employed the Interacting Boson Model-2 (IBM-2) to determine the most appropriate Hamiltonian for the study of tellurium nuclei. Using the best fit values of parameters to construct the Hamiltonian, we have estimated energy levels and electromagnetic transitions (B(E2), B(M1)), multipole mixing ratios (δ(E2/M1)) for some doubly-even Te nuclei and monopole transition probability. The results are compared with previous experimental and theoretical data and it is observed t hat they are in good agreement.

Key words: *Interacting boson model, electromagnetic transition probabilities, mixing ratios, electric monopole transitions.*

INTRODUCTION

There have been many attempts to explore the factors responsible for the onset of large deformation in nuclei of the mass region A>100. The Interacting Boson Model (IBM) is one of those attempts that has been successful in describing the low-lying nuclear collective motion in medium and heavy mass nuclei [1–3]. The purpose of this paper is to set up some even-even nuclei around the mass region $A \approx 120$. The neutron rich -even Te isotopes around the mass region $A \approx 120$ are very important for understanding the gradual change from spherical to a deformed state via transitional phase [4]. These nuclei rather they lie beyond doubly magic Sn^{132}, near which structural changes are rather rapid with changes in the proton and neutron numbers.

The outline of the remaining part of this paper is as follows. Starting from an approximate IBM-2 formulation for the Hamiltonian, we review the theoretical background of the study. Previous experimental and theoretical data are compared with estimated values and the general features of Te isotopes in the range A= 120–128.

In recent years many works have been done on the structure of tellurium nucleus in recent years; Lopac (1970) [5] studied on semi-microscopic description of even tellurium isotopes, Degrieck and Berghe (1974) [6] determined structure and electromagnetic properties of the doubly even Te isotopes, Sambataro (1982) [7] calculated the some of electromagnetic properties of Te and Cd isotopes with the framework of the interacting boson approximation, Subber et al. (1987) [8] apply the dynamic deformation model (DDM) to the tellurium isotopes, Rikovska et al. (1987) [9]. Studied dynamical symmetries in even-even Te nuclides, Yazar and Uluer (2007) [10] studied energy levels, electromagnetic transition properties and mixing ratios of tellurium isotopes.

The aim of this work is to calculate the energy levels and electromagnetic transitions probabilities B(E2) and B(M1), multipole mixing ratios and monopole matrix elements in deformed Te isotopes, using the IBM-2, and to compare the results with the experimental data.

2- Theoretical Consideration

It is proposed that the change from spherical to deformed structure is related to an exceptionally strong neutron-proton interaction. It is also suggested that the neutron-proton effective interactions have a deformation producing tendency, while the neutron-neutron and proton-proton interactions are of spheriphying nature [11,12]. Within the region of medium-heavy and heavy nuclei, a large of nuclei exhibit properties that are neither close to anharmonic quadrupole vibrational spectra nor to deformed rotors [13]. While defining such nuclei in a geometric description [14], these phenomena will have a standard description that is given in terms of nuclear triaxiality [15], going from rigid triaxial shapes to softer potential energy surfaces. In the first version of the interacting boson model (IBM-1) [16,17], no distinction is made between proton and neutron variables while describing triaxiality explicitly. This can be done by introducing the cubic terms in the boson operators [18,19]. This is a contrast to the recent work of Dieperink and Bijker [21, 22] who showed that triaxiality also occurs in particular dynamic symmetries of the IBM-2 that does distinguish between protons and neutrons.

According to A. Arima et al. [23], IBM Hamiltonian takes on different forms, depending on the regions (SU(5), SU(3), O(6)) of the traditional IBM triangle. The Hamiltonian that we consider is in the form [19,20].

$$H = EPS.n_d + PAIR.(P.P) + \frac{1}{2}ELL.(L.L) + \frac{1}{2}QQ.(Q.Q)$$
$$+ 5OCT.(T_3.T_3) + 5HEX.(T_4.T_4)\text{.......................}(1)$$

In the Hamiltonian, d-boson energy ($EPS = \varepsilon_d$), n_d (number of d-boson) and P.P terms produce the characteristics of U(5) and O(6) structures, respectively. So the Hamiltonian is a mixture of the U(5) and SO(6) chains, but not diagonal in any of the IBM chains. In the IBM–2 model the neutrons' and protons' degrees of freedom are taken into account explicitly. Thus the Hamiltonian [24] can be written as

$$H = \varepsilon(\tilde{n}_{d_\nu} + \tilde{n}_{d_\pi}) + \kappa.Q_\nu.Q_\pi + \tilde{\kappa}(Q_\nu.Q_\nu + Q_\pi.Q_\pi) + V_{\nu\nu} + V_{\pi\pi} + M_{\nu\pi} \tag{2}$$

Where ε is the d-boson energy, κ is the strength of the quadrupole interaction between neutron and proton bosons, $\rho = \nu, \pi$, χ_ρ is the quadrupole deformation parameter for neutrons ($\rho = \nu$) and protons ($\rho = \pi$). The last term $M_{\nu\pi}$ is the Majorana force, which has the form:

$$M_{\nu\pi} = \tfrac{1}{2}\xi_2(s_\nu^+ d_\pi^+ - d_\nu^+ s_\pi^+)^{(2)}.(\tilde{s}_\nu \tilde{d}_\pi - \tilde{d}_\nu \tilde{s}_\pi)^{(2)} - \sum_{k=1,3}\xi_k (d_\nu^+.d_\pi^+)^{(k)}.(\tilde{d}_\nu.\tilde{d}_\pi)^{(2)} \tag{3}$$

The term $\tilde{\kappa}(Q_\nu.Q_\nu + Q_\pi.Q_\pi)$ is a quadrupole interaction among similar bosons. This part of the interaction introduces a triaxial component into the IBM-2 Hamiltonian when χ_ν and χ_π have opposite signs. This is the main deference between this Hamiltonian and the usual IBM-2 Hamiltonian.

In the IBM-2 model, the quadrupole moment operator is given by [25]:

$$Q_\rho = (s_\rho^+ d_\rho^\sim + d_\rho^+ s_\rho)^{(2)} + \chi_\rho (d_\rho^+ d_\rho^\sim)^{(2)} \tag{4}$$

The general one-body E2 transition operator in the IBM-2 is:

$$T(E2) = e_\nu.Q_\nu + e_\pi.Q_\pi \tag{5}$$

Where Q_ρ is in the form of equation (4). For simplicity, the χ_ρ has the same value as in the Hamiltonian [26]. This is also suggested by the single j-shell microscopy. In general, the E2 transition results are not sensitive to the choice of e_ν and e_π, whether $e_\nu = e_\pi$ or not.

The B (E2) strength for E2 transitions is given by:

$$B(E2; I_i \to I_f) = 1/(2I_i + 1)^{1/2}\left(\left| < I_f \| T(E2) \| I_i > \right|^2\right) \tag{6}$$

In the IBM-2, the M1 transition operator up to the one-body term is

$$T(M1) = \sqrt{\frac{3}{4\pi}}(g_\nu.L_\nu + g_\pi.L_\pi) \tag{7}$$

The g_ν and g_π are the boson g-factors that depend on the nuclear configuration. They should be different for different nuclei. Where $L_\upsilon(L_\pi)$ is the neutron and (proton) angular momentum operator $L_p{}^{(1)} = \sqrt{10}(d^+d)^{(1)}$.

Instead of evaluate the E2 and M1 matrix elements for the Te isotopes under study which are essential in the theoretical mixing ratio calculations, it is possible to determine these ratios in an analytical form. The calculated reduced E2/M1 mixing ratio:

$$\Delta(\mathrm{E2/M1}) = \frac{\langle \mathrm{I_f} \| \mathrm{T(E2)} \| \mathrm{I_i} \rangle}{\langle \mathrm{I_f} \| \mathrm{T(M1)} \| \mathrm{I_i} \rangle} \tag{8}$$

are related to mixing ratios, $\delta(\mathrm{E2/M1})$ by

$$\delta(\mathrm{E2/M1}) = 0.835\mathrm{E}_\gamma \Delta(\mathrm{E2/M1}) , \tag{9}$$

Where E_γ is called the transition energy and in MeV and $\Delta(\mathrm{E2/M1})$ is in $(\mathrm{eb}/\mu_\mathrm{n})$.

A monopole transition (E0) is given by of Subber *et a1* [8] may now be undertaken and we monopole transition operator as:

$$T(E0) = \beta_{0\rho}(d^+ \times d)^{(0)}_\rho + \gamma_{o\rho}(s^+ \times s)^{(0)}_\rho \text{..............}(10)$$

which is related to the $\rho(E0)$ transition matrix by the expression where R=1.25*10^{-15} m.

$$\rho_{if}(E0) = \frac{Z}{R_o^2} \sum \beta^-_{0\rho} < f \left| d^+_\rho \times d_\rho \right| i > \text{..........}(11)$$

$$B(E0; J_i^+ \to J_f^+) = e^2 R_o^2 \rho^2(E0) \text{..........}(12)$$

In most cases we have to determine the intensity ratio of E0 to the competing E2 transition calling this as $X(\frac{E0}{E2})$ value [14] which can be written as

$$X(E0/E2) = \frac{B(E0; I_i \to I_f)}{B(E2; I_i \to I_{f'})} \text{............................}(13)$$

where $I_f = I_{f'}$ for $I_i \neq 0, and\ I_f = 0, I_{f'} = 2\ for\ I_i = 0.$

RESULTS AND DISCUSSION

3.1- IBM-2 Hamiltonian Parameters

The computer program NPBOS [28] was used to make the Hamiltonian diagonal. In principle, all parameters can be varied independently in fitting the energy spectrum of one nucleus. However, in order to reduce the number of free parameters and in agreement with microscopic calculations of Subber et al., [7], only ε and κ are vary as a function to both of N_π and N_ν *i.e.* $\varepsilon = \varepsilon(N_\pi, N_\nu)$ and $\kappa = \kappa(N_\pi, N_\nu)$ are allowed . The other parameters depend only on N_π or N_ν, *i.e.*

$\chi_\pi = \chi_\pi(N_\pi)$, $\chi_\nu = \chi_\nu = (N_\nu)$, $C_{L\pi} = C_{L\pi}(N_\pi)$ and $C_{L\nu} = C_{L\nu}(N_\nu)$

Thus, in isotopes chain, χ_π is kept constant , whereas for two isotonic Te isotopes, χ_ν, $C_{L\pi}$ and $C_{L\nu}$ are kept constant (see table 1).

The isotopes $^{122-128}$Te have $N_\pi = 1$, and N_ν varies from 6 to 3, while the parameters κ, χ_ν, χ_π and ε were treated as free parameters and their values were estimated by fitting to the measured level energies. This procedure was made by selecting the “traditional” values of the parameters and then allowing one parameter to vary while keeping the others constant until a best fit was obtained. This was carried out iteratively until an overall fit was achieved. The best fit values for the Hamiltonian parameters are given in Table 1.

Table 1: IBM-2 Hamiltonian parameters , all parameters in MeV units

Nuclei	ε	κ	χ_π	χ_ν	$C_{0\nu}$	$C_{2\nu}$	$C_{4\nu}$	$C_{0\pi}$	$C_{2\pi}$	$C_{4\pi}$
$^{122}_{52}Te_{70}$	0.503	0.008	0.02	0.01	0.002	0.003	0.002	0.002	0.003	0.002
$^{124}_{52}Te_{72}$	0.508	0.010	0.02	0.01	0.002	0.003	0.002	0.002	0.003	0.002
$^{126}_{52}Te_{74}$	0.602	0.020	0.03	0.02	0.002	0.003	0.002	0.002	0.003	0.002
$^{128}_{52}Te_{76}$	0.621	0.022	0.03	0.02	0.002	0.003	0.002	0.002	0.003	0.002

$$\xi_1 = \xi_3 = -0.09MeV \qquad \xi_2 = 0.123MeV$$

3.2- Energy levels

Using the parameters in Table 1, the estimated energy levels are shown in Table 2, along with experimental energy levels. As can be seen, the agreement between experiment and theory is quite good and the general features are reproduced well. We observe the discrepancy between theory and experiment for high spin states. But one must be careful in comparing theory with experiment, since all calculated states have a collective nature, whereas some of the experimental states may have a particle-like structure. Behavior of the ratio $R_{4/2} = E(4_1^+)/E(2_1^+)$ of the energies of the first 4^+ and 2^+ states are good criteria for the shape transition[27]. The value of $R_{4/2}$ ratio has the limiting value 2.0 for a quadrupole vibrator, 2.5 for a non-axial gamma-soft rotor and 3.33 for an ideally symmetric rotor. $R_{4/2}$ remain nearly constant at increase with neutron number. The estimated values change from about 2.18 to about 2.26, meaning that their structure seems to be varying from axial gamma soft to quadrupole vibrator $O(6) \rightarrow SU(5)$.

Since Te nucleus has a rather vibrational-like character, taking into account of the dynamic symmetry location of the even-even Te nuclei at the IBM phase Casten triangle where their parameter sets are at the $O(6) \rightarrow SU(5)$ transition region and closer to SU(5) character and we used the multiple expansion form of the Hamiltonian for our approximation.

Table 2: Energy levels for $Te^{122-128}$ (in MeV unit)

J_i^π	Te^{122}		Te^{124}		Te^{126}		Te^{128}	
	Exp.	IBM-2	Exp.	IBM-2	Exp.	IBM-2	Exp.	IBM-2
0_1^+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2_1^+	0.5641	0.563	0.602	0.602	0.666	0.662	0.743	0.749
0_2^+	1.9405	1.453	1.156	1.234	1.878	1.741	1.982	1.977
4_1^+	1.1813	1.182	1.248	1.278	1.316	1.320	1.498	1.492
2_2^+	1.2568	1.291	1.325	1.347	1.420	1.520	1.512	1.497
3_1^+	2.432	2.550	-	1.864	-	2.003	-	2.108
6_1^+	1.7514	1.699	1.747	2.001	1.776	1.891	1.811	1.853
4_2^+	1.9090	1.721	1.957	2.109	2.014	2.211	-	2.231
2_3^+	1.7526	2.569	2.039	2.531	2.190	2.241	-	2.262
4_3^+	2.0401	2.320	2.224	2.623	2.733	2.575	-	2.851

Experimental data are given from Ref. [29].

3.3- Electric Transition Probability *B(E2)*

In order to find the value of the effective charge we have fitted the calculated absolute strengths $B(E2;2_1^+ \rightarrow 0_1^+)$) the transitions ground state band to the experimental ones. The values of the boson effective charges for all isotopes, following the work of Sambataro and Molnar on the Mo isotopes) were determined by the experimental $B(E2;2_1^+ \to 0_1^+)$, we obtained the effective charges that $e_\nu = 0.105$ e.b and $e_\pi = 0.185$ e.b. Table 3 given the electric transition probability .

The $B(E2;2_1^+ \to 0_1^+)$ and $B(E2;4_1^+ \to 2_1^+)$ values decrease as neutron number increases toward the middle of the shell as the value of $B(E2;2_2^+ \to 2_1^+)$ has small value because contain mixtures of M1. The value of $B(E2;2_2^+ \to 0_1^+)$ is small because this transition is forbidden (from quasibeta band to ground state band).

The quadrupole moment for first excited state in Te isotopes are very well described. As mentioned above, the calculated values of $Q(2_1^+)$ indicated this nucleus has prolate shape in first excited states.

Table 3: Electric transition probability for Te $^{122-128}$ in e^2b^2 units

$J_i^\pi \to J_f^\pi$	Te^{122}		Te^{124}		Te^{126}		Te^{128}	
	Exp.	***IBM-2***	*Exp.*	***IBM-2***	*Exp.*	***IBM-2***	*Exp.*	***IBM-2***
$2_1^+ \to 0_1^+$	0.132(12)	0.131	0.1138(15)	0.121	0.094(4)	0.082	0.076(6)	0.081
$4_1^+ \to 2_1^+$	0.19	0.186	0.14(36)	0.183	0.159	0.139	-	0.163
$2_2^+ \to 2_1^+$	0.0350(16)	0.0043	0.0340	0.030	0.0200	0.025	-	0.032
$2_2^+ \to 0_1^+$	0.0390(17)	0.0321	0.0033	0.00439	0.0013	0.0019	-	0.0023
$Q(2_1^+)$ *e.b*	-0.50(22)	-0.35	-0.08(11)	-0.102	-0.16(16)	-0.181	-0.14(13)	-0.19

Experimental data are taken from [9,30,,31,32,33]

3.4- Magnetic Transition Probability *B(M1)* and Mixing Ratio *(E2/M1)*

To evaluate the magnetic transition probability, we depend on the eq. 7, and determine the values of g_π and g_ν . It is interesting to note that the matrix element is approximately proportional to $N_\pi/(N_\pi + N_\nu)$ and $N_\nu/(N_\pi + N_\nu)$, respectively , and this is directly to the number of active proton and neutron bosons. This leads to this approximate expression [7]:

$$g = g_\pi N_\pi/(N_\pi + N_\nu) + g_\nu N_\nu/(N_\pi + N_\nu)$$

and $g = Z/A$, where Z is the atomic number, and A is the mass number.

Therefore the values of g-factor is given as $g_\nu = 0.35\mu_N$ and $g_\pi = 0.81\mu_N$ .Table 4 given the values of B(M1) for some transitions, there is no experimental data to compare with IBM-2 results.

1- The transitions between low-lying collective states (e.g., $2_1^+, 2_2^+$) which are relatively weak since the arise from antisymmetric component in the wavefunctions introduced by F-spin breaking in the Hamiltonian.

2- Strong transitions connecting a symmetric states, $|F_{\max}\rangle$ with one proton-neutron boson mixed symmetry (e.g., $B(M1;1^+ \to 0_1^+)$) .

3- The magnitude of M1 values increases with increasing spin for $\gamma \to g$ and $\gamma \to \gamma$ transitions.

Table 4: Magnetic transition probability for Te $^{122-128}$ in μ_N^2 units

$J_i^\pi \to J_f^+$	Te^{122}	Te^{124}	Te^{126}	Te^{128}
	IBM-2	*IBM-2*	***IBM-2***	***IBM-2***
$1^+ \to 0_1^+$	0.832	0.847	0.923	0.830
$2_2^+ \to 2_1^+$	0.000619	0.000752	0.000345	0.000235
$3_1^+ \to 2_1^+$	0.00231	0.00439	0.00561	0.00431
$2_3^+ \to 2_1^+$	0.00011	0.00044	0.00076	0.000329
$2_3^+ \to 2_2^+$	0.000871	0.000881	0.000871	0.000432

We evaluate the mixing ratio $\delta(E2/M1)$ for Te isotopes, depend on the equation (9), from table 5, shows the variation of 6 for the group of $2^+ \to 2_1^+$ transitions and it is seen that both the *magnitude* and *sign* of $\delta(E2/M1)$ are correctly obtained for the three transitions a summary of the results where the experimental data have sufficient precision for a useful comparison and also when there is no ambiguity in the nature of the levels. (At higher energies where the level density is great the order of the experimental levels may differ from the calculated order.).

Table 5: Mixing ratios for Te 122-128 in eb/μ_N units

Transition $J_i^\pi \to J_f^+$	Te^{122}		Te^{124}		Te^{126}		Te^{128}	
	$Exp.$	IBM-2	$Exp.$	IBM-2	$Exp.$	IBM-2	$Exp.$	IBM-2
$2_2^+ \to 2_1^+$	-3.8	-1.56	-3.55	-2.560	$-4.25_{-0.01}^{+0.15}$	-6.981	$4.6_{-1.0}^{+1.6}$	2.562
$4_2^+ \to 4_1^+$	-0.57	0.01	-0.18	-0.210	$0.09 < \delta < 1.8_{-0.4}^{+0.7}$	3.117		3.290
$2_3^+ \to 2_1^+$	-	0.89	-0.26	0.001	-	0.0002	$4.2_{-1.0}^{+2.0}$	3.431
$2_3^+ \to 2_2^+$	-0.3<δ<0.0	-0.025	$1.5_{-0.3}^{+0.6}$	2.98	-	2.569	-	2
$4_3^+ \to 4_1^+$	$1.3_{-0.4}^{+0.3}$	2.34	0.23	0.461	-	0.982	-	-3.45
$4_3^+ \to 4_2^+$	-	2.456	-	3.890	-	-0.452	-	2.431
$3_3^+ \to 4_1^+$	-	-3.561	-	-2.765	-	2.984	1.4	1.940
$3_3^+ \to 2_2^+$	-	-3.870	-	0.861	-	0.567	$0.45_{-1.2}^{+2.5}$	1.357

Experimental data are taken from [34]

3.5- Monopole matrix element $\rho(E0)$

The necessary parameters of the monopole matrix element are derived from the values of isotopic shift $\Delta < r^2 >= 0.18(13)$ [30] for the ${}_{52}Te_{70}^{122} - {}_{52}Te_{72}^{124}$. We obtain $\beta_{0\pi} = -8.6 * 10^{-3}\ fm^2$, $\beta_{0\nu} = -6.8 * 10^{-3}\ fm^2$ and $\gamma_{0\nu} = -47 * 10^{-3}\ fm^2$. Table *6* contains the calculated $\rho(E0)$ values. In general there is no experimental data to compare with the IBM-2 calculations**.**

Table 6: Monopole matrix element Te 122-128

$J_i^\pi \to J_f^+$	Te^{122}	Te^{124}	Te^{126}	Te^{128}
	IBM-2	IBM-2	IBM-2	IBM-2
$0_2^+ \to 0_1^+$	2.450	2.690	0.057	0.028
$2_2^+ \to 2_1^+$	0.023	0.028	0.027	0.021
$0_3^+ \to 0_2^+$	0.236	0.220	0.211	0.120

Table 7: Calculated *X(E0/E2)* ratios compare with experimental data in even Te isotopes.

Transition $J_i^\pi \to J_f^+$	Te^{122}	Te^{124}	Te^{126}	Te^{128}
	IBM-2	IBM-2	IBM-2	IBM-2
$0_2^+ \to 0_1^+$	0.380	0.080	0.019	0.004
$2_2^+ \to 2_1^+$	0.648	0.181	0.065	0.046
$0_3^+ \to 0_1^+$	0.046	2.694	5.027	0.805
$0_3^+ \to 0_2^+$	3.605	4.134	0.308	0.800

We notice that most of the theoretical values for the $X(E0/E2)$ ratio are small, (see table 7) which means that there is a small contribution of E0 transition on the life time of the 0^+ states. There are two high values of X in transitions from 0_2^+ to 0_1^+ in Te isotopes means that this state decay mostly by the E0 and according to this one could say that the study of this state give information about the shape of the nucleus, because the E0 transitions matrix elements connected strongly with the penetration of the atomic electron to the nucleus. So combination of the wave function of atomic electron, which is well known, and the nuclear surface give good information of the nuclear shape.

CONCLUSION

The low-energy level structure of Te isotopes offers a difficult challenge to several aspects of nuclear structure. The IBM-2 calculations provide a satisfactory framework for describing the nucleus with a structure lying between the O(6) and U(5) limits.

The IBM-2 electric transition probability $B(E2; I_i^+ \rightarrow I_f^+)$ calculations for even-even Te isotopes were in better agreement with the experimental data. The best fit values for the Hamiltonian parameters for even-even tellurium isotopes are given in Table 1. $B(E2)'s$ is good for ground state band and we hope that if the other parameters are normalized by means of this projection it can be considerably improved for beta and gamma band**.** The behavior of the parameters indicates that the nuclei shapes change as function of neutron number**.**

In this work we examine the magnetic transition probability B(M1) for number of set of states, the results shows that. The transitions between low-lying collective states which are relatively weak since the arise from antisymmetric component in the wavefunctions introduced by F-spin breaking in the Hamiltonian. The magnitude of M1 values increases with increasing spin for $\gamma \rightarrow g$ and $\gamma \rightarrow \gamma$ transitions.

We have also examined the mixing ratio $\delta(E2/M1)$ of transitions linking the gamma band and ground state bands. The transitions which link low spin states and were obtained in the present work are in good agreement and show a little bit irregularities.

The 2_2^+ could be interpreted as a band-head of gamma- band linked with a strong B(E2) transition, which suggests that they are collective or forming gamma rotational band based on the 2_2^+ band head.

The intruder 0_2^+ which becomes the first excited state in Te is a band head of strongly deformed band, coexisting with a less deformed structure of nucleus. The IBM-2 version was able to reproduce $\delta(E2/M1)$ for most transitions especially $2_2^+ \rightarrow 2_1^+$, with its sign.

The IBM-2 Calculated and experimental energies, B(E2), B(M1), quadrupole moment for first excited state, and multipole mixing ratios (δ(E2/M1)) and monopole matrix elements for many transition are mostly in agreement with each other.

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