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SEARCH ON RESULTS OF IBM FOR REGION BETWEEN 120 ≤ A ≤ 150: $^{120\text{-}128}$Te AND $^{122\text{-}134}$ Xe NUCLEI

Nureddin Turkan[1], Ismail Maras[2]
[1]Bozok University, Faculty of Arts and Science, Yozgat, Turkey,
[2]Celal Bayar University, Department of Physics, Manisa, Turkey
nurettin_turkan@yahoo.com, maras.ismail@yahoo.com

Abstract -In this work, the energy levels and transition probabilities *B(E*2*)* of some even-even Te (*Z*=52, *N*=68-80 and *N*=84) and even-even Xe nuclei (*Z*=54, *N*=68-80 and *N*=84-88) have been investigated by using the interacting boson model (IBM-1 and IBM-2). The results were compared with some previous experimental and theoretical values. It was seen that an acceptable degree of agreement between the predictions of the model (IBM-1 and IBM-2) and the experiment is achieved.
Key Words- Interacting boson model, Transition probability, Energy level.

1. INTRODUCTION

The interacting boson model [1] is a valuably interpretive model aiding to understand the nuclear structure. IBM defines six-dimensional space described by in terms of unitary group, *U*(6). Different reductions of *U*(6) gives three dynamical symmetry limits known as harmonic oscillator, deformed rotor and asymmetric deformed rotor which are labeled by *U*(5), *SU*(3) and *O*(6) respectively [2]. However, one should not confuse the symmetry triangle of the IBM [3,4] to the triangle of the collective model [5,6,7] in which *X*(5) and *E*(5) appear. In the present study, the interacting boson model is used as a method of solution and the new different parameters of IBM-1 and IBM-2 are used to describe the structures of 120-132Te, 136Te, 122-134Xe and 138-142Xe isotopes.

Recently, the Xe [8–17] and Te [18–25] region with the mass number A ≅120–140 has been studied experimentally and interpreted by several models [23–28]. The ground state properties of even–even Xe isotopes have been the subject to theoretical and experimental studies [29–37] involving in-beam γ -ray spectroscopy. Very little is known about the multipolarities of interband transitions in tellurium nuclei. In order to explain these large Q(2+) values, a considerable amount of theoretical work has been developed.

The low-lying states showing a rich collective structure in this region, were investigated extensively in terms of various models, such as the interacting boson model (IBM) [1,8,24,38-42], the fermion dynamical symmetry model (FDSM) [43,44], the pair-truncated shell model (PTSM) [45-47] and the nucleon-pair shell model [48-51]. The outline of the remaining part of this paper is as follows: starting from an approximate theoretical background of the model, we give the basic formulations defined in the IBM-1 and IBM-2 in Section 2. Then, the previous experimental and theoretical [9,15-22,25–29] data are compared with the calculated values and the general features of even-even Te and Xe isotopes in the range *A*=120-132, *A*=136 for Te and *A*=122-134, *A*=138-142 for Xe are reviewed in Section 3. The last section contains some concluding remarks.

2. THEORY

2.1. IBM-1 Model

The IBM-1 model describes the low-lying energy states of the even-even xenon nuclei as a system of interacting *s*-boson and *d*-boson. The most general Hamiltonian that has been used to calculate the level energies is [1-3],

$$H_{sd} = \varepsilon_d \eta_d + \kappa Q\cdot Q + \kappa L\cdot L + \kappa P\cdot P + q_3 T_3\cdot T_3 + q_4 T_4\cdot T_4, \tag{1}$$

where

$$Q\cdot Q = \sqrt{5}\left[\left\{(s^\dagger \tilde{d} + d^\dagger s)^{(2)} - \frac{\sqrt{7}}{2}(d^\dagger \tilde{d})^{(2)}\right\}.\left\{(s^\dagger \tilde{d} + \tilde{d} s)^{(2)} - \frac{\sqrt{7}}{2}(d^\dagger \tilde{d})^{(2)}\right\}\right]^{(0)}_0,$$

$$L\cdot L = -10\sqrt{3}\left[(d^\dagger \tilde{d})^{(1)} . (d^\dagger \tilde{d})^{(1)}\right]^{(0)}_0, \tag{2}$$

$$P\cdot P = \left[\left\{(s^\dagger s^\dagger)^{(0)}_0 - \sqrt{5}(d^\dagger d^\dagger)^{(0)}_0\right\}.\left\{(ss)^{(0)}_0 - \sqrt{5}(\tilde{d}\tilde{d})^{(0)}_0\right\}\right]^{(0)}_0 \tag{3}$$

$$T_3\cdot T_3 = -\sqrt{7}\left[(d^\dagger \tilde{d})^{(2)} . (d^\dagger \tilde{d})^{(2)}\right]^{(0)}_0, \quad T_4\cdot T_4 = 3\left[(d^\dagger \tilde{d})^{(4)} . (d^\dagger \tilde{d})^{(4)}\right]^{(0)}_0 \tag{4}$$

2.2. IBM-2 Hamiltonian

The IBM-2 Hamiltonian that has been used to calculate the level energies is [4],

$$H = \varepsilon_\nu n_{d\nu} + \varepsilon_\pi n_{d\pi} + \kappa Q_\pi Q_\nu + V_{\pi\pi} + V_{\nu\nu} + M_{\pi\nu} \tag{5}$$

where $n_{d\rho}$ is the neutron (proton) *d*-boson number operator.

$$n_{d\rho} = d^\dagger \tilde{d}\ , \rho = \pi, \nu$$

$$\tilde{d}_{\rho m} = (-1)^m d_{\rho,-m} \tag{6}$$

where $s^\dagger{}_\rho$, $d^\dagger{}_{\rho m}$ and $s_\rho, d_{\rho m}$ represent the s and d-boson creation and annihilation operators. The rest of the operators in the Eq.(5) are defined as

$$Q_\rho = (s^\dagger_\rho \tilde{d}_\rho + d^\dagger_\rho s_\rho)^{(2)} + \chi_\rho (d^\dagger_\rho \tilde{d}_\rho)^{(2)}$$

$$V_{\rho\rho} = \sum_{L=0,2,4} C_{L\rho}\, ((d^\dagger_\rho d^\dagger_\rho)^{(L)} \cdot (d^\dagger_\rho \tilde{d}_\rho)^{(L)})^{(0)} \quad ; \ \rho = \pi, \nu \tag{7}$$

$$M_{\nu\pi} = \frac{1}{2}\xi_2[(s^\dagger_\nu d^\dagger_\pi - d^\dagger_\nu s^\dagger_\pi)^{(2)}.(s_\nu \tilde{d}_\pi - \tilde{d}_\nu s_\pi)^{(2}] - \sum_{L=1,3} \xi_L [(d^\dagger_\nu d^\dagger_\pi)^{(L)}. (\tilde{d}_\nu \tilde{d}_\pi)^{(L)}] \tag{8}$$

In this case $M_{\pi\nu}$ affects only the position of the non-fully symmetric states relative to the symmetric ones. For this reason $M_{\nu\pi}$ is often referred to Majorana force.

2.3. B(E2) Transition

As appropriate physical quantities we have used intraband $B(E2)$ ratios as well as quadrupole moment ratios within the low-lying state bands. The electric quadrupole transition operator [52] employed in this study is given by,

$$T(E2) = e_\pi Q^\chi_\pi + e_\nu Q^\chi_\nu \tag{9}$$

where

$$Q^{\chi}_{\rho} = e_{\rho} (d^{\dagger}_{\rho} x s_{\rho} + s^{\dagger}_{\rho} x \tilde{d}_{\rho})^{(2)} + \chi_{\rho} (d^{\dagger}_{\rho} x \tilde{d}_{\rho})^{(2)} \qquad (10)$$

In this expression χ_ρ is a dimensionless coefficient and e_ρ are the effective quadrupole charges. Thus, the reduced electric quadrupole transition rates between $I_i \rightarrow I_f$ states are given by

$$B(E2; I_i \rightarrow I_f) = \frac{\left\lfloor \langle I_f \| T(E2) \| I_i \rangle \right\rfloor}{2I_i + 1} \qquad (11)$$

3. CALCULATIONS

This section has been divided into two parts describing energy spectra and electromagnetic transition rates in such Te and Xe isotopes separately.

3.1. Energy Spectra

The Tables 1 and 2 contain the IBA-1 and IBM-2 Hamiltonians' parameters (in MeV) used in the present study to calculate the energies of the positive parity low-lying levels of $^{120-128}$Te, $^{122-134}$Xe and $^{138-142}$Xe isotopes. N_π=1 and N_ν changes from 7 to 1 for Te isotopes $^{120-128}$Te. Moreover, the Xenon isotopes have N_π=2 while N_ν varies from 8 to 1 for $^{122-134}$Xe and finally varies from 1 to 3 for $^{138-142}$Xe. The Hamiltonian parameter values of IBM-1 and IBM-2 were estimated by fitting to the experimental energy levels and it was made by allowing one parameter to vary while keeping the others constant. This procedure was carried out iteratively until an overall fit was achieved.

Table 1. Parameters used in IBM-1 Hamiltonian for $^{120-128}$Te, $^{122-134}$Xe and $^{138-142}$Xe nuclei (in MeV).

$^{A}_{Z}X$	N	EPS	ELL	QQ	CHQ	OCT	HEX
$^{120}_{52}Te_{68}$	8	0.819	-0.0059	-0.030	-1.1	-0.0011	-0.0078
$^{122}_{52}Te_{70}$	7	0.787	-0.0059	-0.030	-1.1	-0.0011	-0.0078
$^{124}_{52}Te_{72}$	6	0.792	-0.0059	-0.030	-1.1	-0.0011	-0.0078
$^{126}_{52}Te_{74}$	5	0.823	-0.0059	-0.030	-1.1	-0.0011	-0.0078
$^{A}_{Z}X$	N	EPS	ELL	QQ	CHQ	OCT	HEX
$^{122}_{54}Xe_{68}$	9	0.640	-0.0059	-0.030	-1.1	-0.0011	-0.0078
$^{124}_{54}Xe_{70}$	8	0.616	-0.0042	-0.030	-1.1	-0.0011	-0.0078
$^{126}_{54}Xe_{72}$	7	0.561	-0.0059	-0.030	-1.1	-0.0011	-0.0078
$^{128}_{54}Xe_{74}$	6	0.630	-0.0059	-0.030	-1.1	0.0011	-0.0078
$^{130}_{54}Xe_{76}$	5	0.692	-0.0059	-0.030	-1.1	-0.0011	-0.0085
$^{132}_{54}Xe_{78}$	4	0.792	-0.0059	-0.030	-1.1	-0.0011	-0.0078

${}^{134}_{54}Xe_{80}$	3	0.943	-0.0059	-0.030	-1.1	-0.0011	-0.0078
${}^{138}_{54}Xe_{84}$	3	0.683	-0.0059	0.030	-1.1	-0.0030	-0.0078
${}^{140}_{54}Xe_{86}$	4	0.498	-0.0059	-0.055	-1.1	-0.0011	-0.0078
${}^{142}_{54}Xe_{88}$	5	0.438	-0.0059	-0.050	-1.1	0.0000	-0.0078

Except the IBM-2 parameter values for ${}^{122-134}Xe$, we did the IBM-1 calculations using code PHINT [53] and IBM-2 by code NP-BOS [54] with our own parameters.

Table 2. Parameters used in IBM-2 Hamiltonian for ${}^{120-128}Te$, ${}^{122-134}Xe$ [16] and ${}^{138-142}Xe$ nuclei (in MeV).

${}^{A}_{Z}X$	N_π	N_ν	N	ε	κ	χ_ν	χ_π	**$C_{L\nu}$** (L=0,2,4)	**$C_{L\pi}$** (L=0,2,4)
${}^{120}_{52}Te_{68}$	1	7	8	0.70	-0.08	0.8	-1.2	0	0
${}^{122}_{52}Te_{70}$	1	6	7	0.70	-0.08	0.5	-1.2	0	0
${}^{124}_{52}Te_{72}$	1	5	6	0.73	-0.08	0.8	-1.2	0	0
${}^{126}_{52}Te_{74}$	1	4	5	0.80	-0.09	0.2	-1.2	0	0
${}^{128}_{52}Te_{76}$	1	3	4	0.80	-0.06	0.9	-1.2	0	0
${}^{122}_{54}Xe_{68}$*	2	7	9	0.62	-0.09	0.3	-1.2	0	0
${}^{124}_{54}Xe_{70}$*	2	6	8	0.60	-0.08	0.5	-1.2	0	0
${}^{A}_{Z}X$	N_π	N_ν	N	ε	κ	χ_ν	χ_π	**$C_{L\nu}$** (L=0,2,4)	**$C_{L\pi}$** (L=0,2,4)
${}^{126}_{54}Xe_{72}$*	2	5	7	0.59	-0.08	1.2	-1.2	0	0
${}^{128}_{54}Xe_{74}$*	2	4	6	0.64	-0.08	0.4	-1.2	0	0
${}^{130}_{54}Xe_{76}$*	2	3	5	0.72	-0.08	0.4	-1.2	0	0
${}^{132}_{54}Xe_{78}$*	2	2	4	0.700	-0.080	0.3	-1.2	0	0
${}^{134}_{54}Xe_{80}$*	2	1	3	0.940	-0.080	0.2	-1.2	0	0
${}^{138}_{54}Xe_{84}$	2	1	3	0.676	-0.080	1.2	-1.2	0	0
${}^{140}_{54}Xe_{86}$	2	2	4	0.500	-0.085	1.2	-1.2	0	0
${}^{142}_{54}Xe_{88}$	2	3	5	0.500	-0.250	1.2	-1.2	0	0

*[16]

Where; N= number of bosons, EPS = ε_d, ELL = $\sqrt{10}$ T_1, QQ = 2κ, OCT = $T_3.T_3$,

HEX = $T_4.T_4$ and CHQ = $\left[\left\{(d^\dagger s + s^\dagger \tilde{d})^{(2)} - \frac{\sqrt{7}}{2}(d^\dagger \tilde{d})^{(2)}\right\}\right]$

3.2. Electromagnetic Transition rates

The stable even-even nuclei in Te, Xe, Ce and Nd isotopic chains represent excellent opportunities for studying the behavior of the total low-lying E2 strengths in the transitional region from deformed to spherical nuclei. After having obtained wave functions of the states, we can calculate the electromagnetic transition rates between low-lying states of all chain for $^{120\text{-}128}$Te and $^{122\text{-}134}$Xe isotopes. Calculation of electromagnetic transitions is a sign of good test for the nuclear model wave functions. To determine the boson effective charges $e_\rho(\rho = \pi, \nu)$ we perform a fit to the experimental $B(E2)$ values in such isotopes. The matrix elements of the $E2$ operator of Eq.(9) have been calculated by using the following values of effective charge parameters.

In IBM-1 calculations:

Nuclei	E2SD	E2DD	Nuclei	E2SD	E2DD
$^{122}_{54}Xe$	0.12	0.3	$^{120}_{52}Te_{68}$	0.10	0.0
$^{124}_{54}Xe$	0.14	0.0	$^{122}_{52}Te_{70}$	0.27	0.0
$^{126}_{54}Xe$	0.12	0.0	$^{124}_{52}Te_{72}$	0.28	0.0
$^{128}_{54}Xe$	0.14	0.0	$^{126}_{52}Te_{74}$	0.28	0.0
Nuclei	E2SD	E2DD	Nuclei	E2SD	E2DD
$^{130}_{54}Xe$	0.15	0.0	$^{128}_{52}Te_{76}$	0.29	0.0
$^{132}_{54}Xe$	0.14	0.0	$^{134}_{54}Xe$	0.15	0.0

Here, proton boson effective charge parameter, e_π is denoted by E2SD and neutron boson effective charge parameter, e_ν is denoted by E2DD. In IBM-2 calculations, the parameter values of Te nuclei are as follows: E2SD=0.28 and E2DD=0.2 for N=68,70,72,74; E2SD=0.29 and E2DD=0.2 for N=76. The effective boson parameter values for IBM-2 calculation of Xe nuclei are taken from [16]. Here, the effective charges appear as new parameters and the units are in eb. So, the Fig. 1 (Fig. 1a for $^{120\text{-}128}$Te isotopes and Fig. 1b for $^{122\text{-}134}$Xe isotopes) shows $B(E2;2_1^+\rightarrow0_1^+)$, $B(E2;4_1^+\rightarrow2_1^+)$ and $B(E2;2_2^+\rightarrow2_1^+)$ transition probabilities calculated in the framework of IBM-1 and IBM-2 for some levels, respectively. In this Fig., the results of the present work were compared with some previous experimental [10,15,51] and theoretical [9,25,51] values and it was seen that they are in good agreement especially for $B(E2;2_1^+\rightarrow0_1^+)$, and $B(E2;4_1^+\rightarrow2_1^+)$. Moreover the general agreement between the calculation and their corresponding experimental values for $B(E2;2_2^+\rightarrow2_1^+)$ transition in Xe nuclei are a little different but reasonable. As it is seen from the Fig., $B(E2)$ values for the transitions of $2_1^+\rightarrow0_1^+$ and $4_1^+\rightarrow2_1^+$ decreases smoothly after the neutron number N=70. They are nicely reproduced by the experiment and the fits of them are satisfactory. Such transitions for both Te and Xe chains are of the same order of magnitude and $B(E2;2_2^+\rightarrow2_1^+)$ is also expected to show the similar distribution. The large $B(E2)$ values in ^{122}Te and in ^{124}Xe nuclei are the main indicator of the vibrational characters. No any experimental $B(E2)$ values exist for $4_1^+\rightarrow 2_1^+$ transitions in Te, and for $2_2^+\rightarrow 0_1^+$ in both Te and Xe chains. To the best of our knowledge they are the ones that are also still not known so far and described naturally by the present work. $B_{4/2}=B(E2;4_1^+\rightarrow 2_1^+)/\ B(E2;2_1^+\rightarrow 0_1^+)$ gives a good systematic of basic observables about intraband structure for $^{120\text{-}128}$Te and $^{122\text{-}134}$Xe isotopes. So, Fig. 1 also indicates the calculated $B_{4/2}$ ratios in IBM-1 and IBM-2, and they are seen reasonably well.

4. CONCLUSIONS

The main points obtained in this paper can be summarized as follows. The positive parity states of even-even Te (Z=52, N=68-80 and N=84) and even-even Xe nuclei (Z=54, N=68-80 and N=84-88) have been discussed within the first and the second version frameworks of interacting boson model and it was seen that they are generally in good agreement with the experimental data. Moreover, most of the calculated values in fig. 1 are much better than the previous theoretical results. The calculated results shown in such figure indicate the elegance of the fits presented in this manuscript and they suggest the success of the guess in parameterization. That is, the sets of parameters used in the calculations for all Te and Xe isotopes are the best approximation that has been carried out so far. Since they give information on structural changes in nuclear deformation and shape-phase transitions, even-even $^{120\text{-}128}$Te are very interesting sequence of nuclei and very few works exist in the literature for them. $B(E2)$ transition probabilities of some even-even Te and Xe isotopes are calculated by using the model perspectives. And then, it was seen that the calculated results have generally nice agreement with experimental and theoretical ones. As a result, it may be concluded that nuclear behaviors of the chains of Te and Xe isotopes are well studied in this work and it was seen that dominant vibrational characters exist in the sequence of even-even Te nuclei. Furthermore, the rotor features also exist in Xe, but with a dominancy of vibrational character. As a recent paper, K. Nomura et al. [55] can be seen to realize the results of different calculation method for Xe region. In that paper, they determines the interacting boson model (IBM) Hamiltonian microscopically for general cases of low-lying quadrupole collectivity by appling it to several other isotopic chains, Ba, Xe, Ru, Pd, W, and Os, in comparison to the experimental data. In their work, the predicted spectra and the B(E2) ratios are presented for heavy neutron-rich exotic nuclei in experimentally unexplored regions such as the right-lower corner of ^{208}Pb on the nuclear chart.

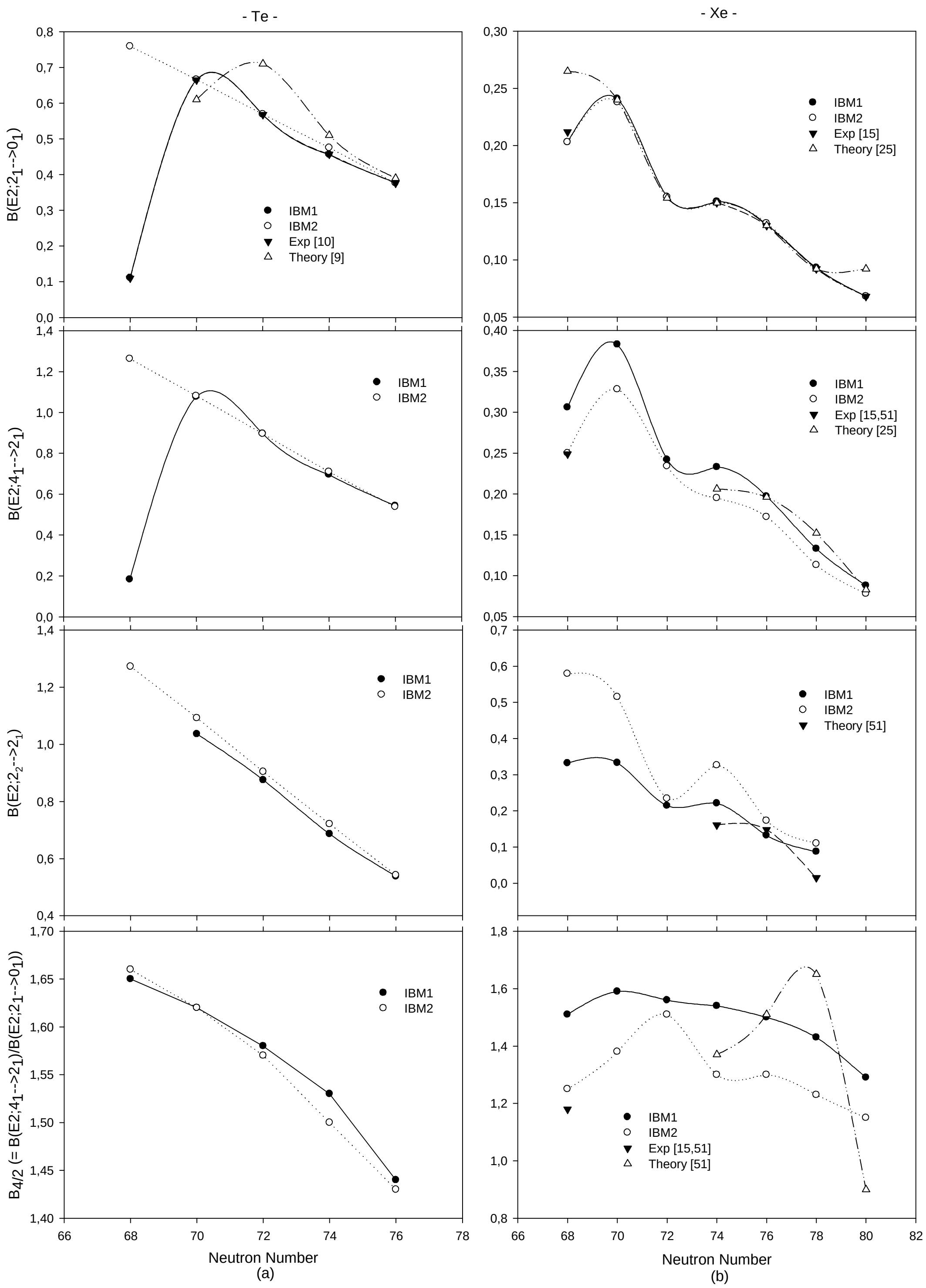

Fig. 1 Comparison of calculated IBM-1 and IBM-2 results of $B(E2;2^+_1\rightarrow0^+_1)$, $B(E2;4^+_1\rightarrow2^+_1)$ and $B(E2;2^+_2\rightarrow2^+_1)$ transition probabilities for **(a)** $^{120\text{-}128}$Te and, **(b)** $^{122\text{-}134}$Xe isotopes. The results of the present work were compared with some previous experimental [10,15,51] and theoretical [9,25,51] values. The figure also indicates the calculated $B_{4/2}$ ratios in IBM-1 and IBM-2 along with theoretical and experimental ones.

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