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Nuclear structure of the odd $^{177-183}$Ta isotopes

Falih H. Al-Khudair*

***Physics Department, Education College for Pure Sciences, Basrah University, Basrah, Iraq*.**

*** E-mail: falih9@gmail.com**

Abstract

The energy of the positive excited states and electromagnetic transition probabilities in neutron-rich $^{177-183}$Ta isotopes have been calculated using interacting boson fermion model (IBFM-2). The wave functions for all states have been investigated. In present model space the fermions are allowed to excite to the $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ single-particle orbitals. It is found that these isotopes can be described by a schematic Hamiltonian of SU(3) limit. The electromagnetic transition probabilities are analyzed which reveal the detailed nature of energy level. The results obtained are in good agreement with available experimental data.

Keywords: odd Ta isotopes (A=177-183), energy level, electromagnetic transitions, IBFM-2

1- Introduction

Many bands have been observed in the A=150-200 region, and as a result, features common to the levels structure of even-even nuclei have become apparent [1-3]. The transition linking the members of the excited bands to the known yrast states are in general observed, thus, crucial information such as spin, parties and energy levels are known experimentally [4-6]. The light Ta isotopes have been established from the spherical proton emitter ^{155}Ta, at the N = 82 shell closure [7]. On the theoretical side, a quantitative and detailed description of nuclear structure for heavy nuclei has been provided by nuclear models, which include the large-scale shell-model [8]. The interacting boson model (IBM) has been used with considerable success in spectroscopic studies of a large set of nuclei with the range Z = 50-82 and N = 82-126 [9,10].

The interacting boson model (IBM) and its various extensions discussed so far, are capable of describing even-even nuclei [11-18]. A simple version of the model in which no distinction between protons and neutron is made. This simple model is called IBM-1 [19-21]. The version of the model in which distinction is made between protons and neutrons is called IBM-2 or proton-neutron IBM [22]. For odd-nuclei, bosons alone are not adequate in describing their nuclear structure because at least one nucleon will always remain uncoupled. The model has been extended to include both bosons and fermions. The extension of IBM including a single fermion in addition to bosons is called the interacting boson fermion model (IBFM), The simple model is called IBFM-1 and the version of the model in which distinction is made between protons and neutrons is called IBFM-2 [23-28].

2-MODEL

To describe the energy levels of the odd-A nuclei in the IBFM-2, an odd nucleon is coupled to a core of proton- and neutron-bosons. The Hamiltonian is written as [22,27]

$$H = H_B + H_F + V_{BF}\ , \tag{1}$$

where H_B is the usual IBM-2 Hamiltonian that describes the system of (s_ν, s_π) and (d_ν, d_π) bosons namely

$$H_B = \varepsilon_d(\hat{n}_{d\pi} + \hat{n}_{d\upsilon}) + k_{\pi\upsilon}\hat{Q}_\pi.\hat{Q}_\upsilon + \sum_{\rho=\pi,\upsilon}\hat{V}_{\rho\rho} + \hat{M}_{\pi\upsilon}\ , \tag{2}$$

where ε_d is the single boson excitation energy. $n_{d\pi}$ and $n_{d\upsilon}$ the number of proton and neutron d-boson operator. $k_{\pi\upsilon}$ Q_π .Q_υ. is the quadruple interaction between proton and neutron boson, where Q_ρ quadruple operator is given by the usual expression

$$\hat{Q} = (d_\rho^+ s_\rho + s_\rho^+ \tilde{d})^{(2)} + \chi_\rho [d_\rho^+ \tilde{d}_\rho]^{(2)} \tag{3}$$

$$\hat{M}_{\pi\upsilon} = \frac{1}{2}\xi_2[(d_\upsilon^+ s_\pi^+ - d_\pi^+ s_\upsilon^+)\cdot(\tilde{d}_\upsilon s_\pi - \tilde{d}_\pi s_\upsilon) + \sum_{k=1,3}\xi_k [d_\upsilon^+ d_\pi^+]^{(k)}\cdot[\tilde{d}_\pi \tilde{d}_\upsilon]^{(k)}, \tag{4}$$

is the Majorana operator, and it separates the full symmetric states from mixed symmetry states. $V_{\rho\rho}$ represents the interaction between like bosons, usually it is

$$\hat{V}_{\rho\rho} = \frac{1}{2}\sum_{L=0,2,4} C_\rho^{(L)}([d_\rho^+ d_\rho^+]^{(L)}\cdot[\tilde{d}_\rho \tilde{d}_\rho]^{(L)}), \quad \rho = \pi,\upsilon \tag{5}$$

The second term in eq. (1)H_F is the fermion Hamiltonian, and it contains only one-body terms,

$$H_F = \sum_i \varepsilon_i n_i \qquad (6)$$

where ε_i is the quasiparticle energy of the *i*th orbital and n_i is the fermion number operator. The quasiparticle energies and occupation probabilities can be obtain by solving the BCS equations as [29]

$$\varepsilon_i = \sqrt{(E_i - \lambda)^2 + \Delta^2} \qquad (7)$$

where λ is the Fermi energy and Δ is the paring gap. The occupation probabilities are then given by

$$\upsilon_i = \left[\frac{1}{2}(1 - \frac{E_i - \lambda}{\varepsilon_i})\right]^{1/2}, \qquad u_i = (1 - \upsilon_i^2)^{1/2} \qquad (8)$$

V_{BF} is the interaction between boson and odd nucleon,

$$V_{BF} = \sum_{i,j} \Gamma_{ij} \left(\left[a_i^+ \tilde{a}_j\right]^{(2)} \cdot Q_{\rho'}^B \right) + A \sum_i n_i n_{d\rho'} + \sum_{i,j} \Lambda_{ki}^{j} \{ : \left[\left[d_\rho^+ \tilde{a}_j \right]^{(k)} a_i^+ s_\rho \right]^{(2)} : \cdot \left[s_{\rho'}^+ \tilde{d}_{\rho'} \right]^{(2)} + H.c. \}, \qquad (9)$$

where Q^B_ρ is the boson quadrupole operator that is defined in Eq. (3). The first term represents the direct component of the quadrupole interaction between the single nucleon and the bosons. The second term is monopole-monopole interaction and the last term is the exchange interaction, which takes into account the effect of the Pauli principle. In order to restrict the number of parameters, the semi-microscopic j - dependence of interactions strengths has been derived [27].

$$\begin{aligned}
\Gamma_{i,j} &= (u_i u_j - \upsilon_i \upsilon_j) Q_{i,j} \Gamma, \\
\Lambda_{k,i}^{j} &= -\beta_{k,i} \beta_{j,k} \left(\frac{10}{N_\rho (2 j_k + 1)} \right)^{1/2} \Lambda, \\
\beta_{i,j} &= (u_i \upsilon_j + \upsilon_i u_j) Q_{i,j}, \\
Q_{i,j} &= \left\langle l_i, \frac{1}{2}, j_i \left\| Y^{(2)} \right\| l_j, \frac{1}{2}, j_j \right\rangle.
\end{aligned} \qquad (10)$$

Electromagnetic transition operators in IBFM-2 have more general than IBM-2. The quadrupole transition operator is defined by [30].The form of electric quadrupole transition operator can be written as

$$T^{E2} = e^B T_B^{E2} + e^F T_F^{E2} \qquad (11)$$

where the boson (*B*) and fermion (*F*) parts can be written

$$T^{E2} = e_\pi^B Q_\pi^B + e_\upsilon^B Q_\upsilon^B + \sum_{i,j} e_{i,j}^F \left[a_i^+ \tilde{a}_j\right]^{(2)}, \qquad (12)$$

where e_ρ and Q_ρ are defined as in IBM-2 and

$$e_{i,j}^F = -\frac{1}{\sqrt{5}}(u_i u_j - \upsilon_i \upsilon_j)\left\langle l_i, \frac{1}{2}, j_i \left\| r^2 Y^{(2)} \right\| l_j, \frac{1}{2}, j_j \right\rangle. \qquad (13)$$

The *M*1 transition operator in IBFM-2 is

$$T^{M1} = \sqrt{\frac{3}{4\pi}}\left(g_\pi^B L_\pi^B + g_\upsilon^B L_\upsilon^B + \sum_{i,j} g_{i,j}^F \left[a_i^+ \tilde{a}_j\right]^{(1)} \right), \qquad (14)$$

where g_ρ and L_ρ are defined as in IBM-2, and $g_{i,j}^F$ is the single-particle contribution, which depends on g_l and g_s for the odd nucleon. $\tilde{L}$ is the angular momentum operator given as

$$\tilde{L}_\rho = \sqrt{10}[\, d^\dagger . \, d]^{(1)} \qquad (15)$$

$$g_{ij}{}^F = -\frac{1}{\sqrt{3}}\left(u_i u_j + \upsilon_i \upsilon_j\right)\left\langle l_i, \frac{1}{2}, j_i \left\| g_l l + g_s s \right\| l_j, \frac{1}{2}, j_j \right\rangle. \qquad (16)$$

The transition strengths from initial state J_i to final state J_f are obtained from the operators of Eqs. (12) and (14) as

$$B(E/M\lambda(J_i \to J_f) = \frac{\left|\left\langle J_f \left\| T^{E/M\lambda} \right\| J_i \right\rangle\right|^2}{(2J_i + 1)}. \qquad (17)$$

3 Energy levels

In the calculation of energy levels in [177-183]Ta isotopes, the proton and neutron shells are assumed to be closed at Z= 82 and N=126 magic shells. The model calculation has been performed, using the core parametrization from the IBM-2 calculation for [178-184]W isotopes, respectively. The Ta isotopes (Z=73), which fill the single particle orbits below the closed shell Z=82, characterized by nine proton hole states. In IBFM-2, the energy levels structure of this isotopes can be described as the result of a proton quasiparticle in the Z = 50 to 82 shell coupled to the W (Z=74) even-even core (proton hole). In the major shell (Z=50-80), there are five single-particle levels, four with positive parity $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, and $3s_{1/2}$, and, and one level with negative parity $1h_{11/2}$. The values of single-particle energies are extracted from Ref. [31], and they are very similar to the ones used in Ref. [32]. The BCS equations are solved with all above five single-particle levels and with $\Delta = 12A^{-1/2}$ [33-36]. The quasiparticle energies for [177-183] Ta isotope are listed in Table 1. It is gratifying to see that most values change fairly slowly with neutron number. The parameters ε_d and $k_{\pi\upsilon}$ have been determined so to reproduce as closely as possible the energy of positive parity low lying states. In addition, the parameters χ_π and χ_υ have effected on the excitation energy and electromagnetic properties, so that are considered $\chi_\pi = \chi_\upsilon = -7^{1/2}/2$, the value reflect SU(3) limit. The strongest influence on the level ordering is that the exchange term. Changing the monopole term A_0, shifts the majority of level energies in a coherent way. The value of parameters were chosen to give the best fit to experimental data are listed in Table 1.

Table 1 : The parameters of the IBFM-2 Hamiltonian for $^{177-183}$Ta nuclei. $\zeta_1 = \zeta_2 = \zeta_3 = 0.080$, $\chi_\pi = \chi_\upsilon = -7^{1/2}/2$ and $A_0 = -0.030$ for all isotopes. All the parameters are in MeV unit, except χ_π and χ_υ which are dimensionless.

A	$\varepsilon(g_{7/2})$	$\varepsilon(d_{5/2})$	$\varepsilon(d_{3/2})$	$\varepsilon(s_{1/2})$	$\varepsilon(h_{11/2})$	$k_{\pi\upsilon}$	ε_d	$C_\pi^L = C_\upsilon^L$ (L=0,2,4)	Γ	Λ
177	2.284	1.375	1.275	1.667	1.082	-0.075	0.330	0.000,-0.100,0.000	0.700	0.300
179	2.279	1.370	1.274	1.667	1.076	-0.075	0.330	0.000,-0.100,0.000	0.850	0.400
181	2.275	1.365	1.272	1.666	1.071	-0.075	0.340	0.000, 0.000, 0.000	1.200	0.400
183	2.271	1.359	1.271	1.666	1.065	-0.062	0.330	0.100,-0.100,-0.150	1.200	0.700

Figures 1 and 2 display a comparison of the results of our IBFM-2 calculations and available experimental
results [37] on the low-lying positive-parity states. The present calculation is successful in reproducing most of the observed levels, with respect to excitation energies, single-particle strength and sequences. At low-lying excitation energy two distinct sets of states are anticipated based on the odd-proton occupying the $g_{7/2}$ and $d_{5/2}$ orbitals. The main component of the ground state $7^+/2$ is the single-quasiparticle state $\pi g_{7/2}$. When a single particle $d_{5/2}$ proton is coupled to the one d-boson states in the $^{178-184}$W nuclei, one obtains the first excited $J^+ = 5^+/2$ state in $^{177-183}$Ta nuclei. Experimentally, the $5^+/2$ and $9^+/2$ is the first excited state in the ^{177}Ta and $^{179-183}$Ta nuclei, respectively.

The calculated results of the energy levels in ^{177,179}Ta are shown in Figure 1. All known experimental levels up to 2.5 MeV are included. For ^{177}Ta, the first and second positive-parity excited states with $J^+ = 5^+/2$ and $9^+/2$ at 0.071 and 0.131 MeV are close to calculated ones at 0.076 and 0.126 MeV, and they are calculated as 89% $d_{5/2} \times 2^+_1$ and 94% $g_{7/2} \times 2^+_1$, respectively. The IBFM-2 calculation predicted the second $7^+/2$ state at 0.181 MeV having a wave function dominated by the $\pi d_{5/2}$ orbit, and the experimental one is at 0.172 MeV. The calculated $7^+/2_3$ appears at 0.661 MeV, but it has yet to be seen in experiment. The $5^+/2_2$ state at 0.653 MeV has been identified with the 0.639 MeV state in the data. The calculated wave functions is 62 $\%d_{3/2}$ + $25\%s_{1/2}$. The character of the state $11^+/2_1$ at 0.288 MeV is $g_{7/2}$ single-particle states and it calculated energy is equal to 0.282 MeV. The first excited state in ^{179}Ta is J^+= $9^+/2$ at 0.131and 0.133 MeV in the model and experimental results, respectively. The calculated excitation energy for the $11^+/2_1$ and $11^+/2_2$ states at 0.293 and 0.627 MeV are close to observed ones at 0.294 and 0.636 MeV, respectively. IBFM-2 calculation predicted the $7^+/2_2$ state at 0.324 MeV which has a wave function dominated by $\pi d_{5/2}$ orbital closed to excremental one at 0.343MeV. The reproduction of the excitation energies for this isotope is a prominent advantage of the present calculation.

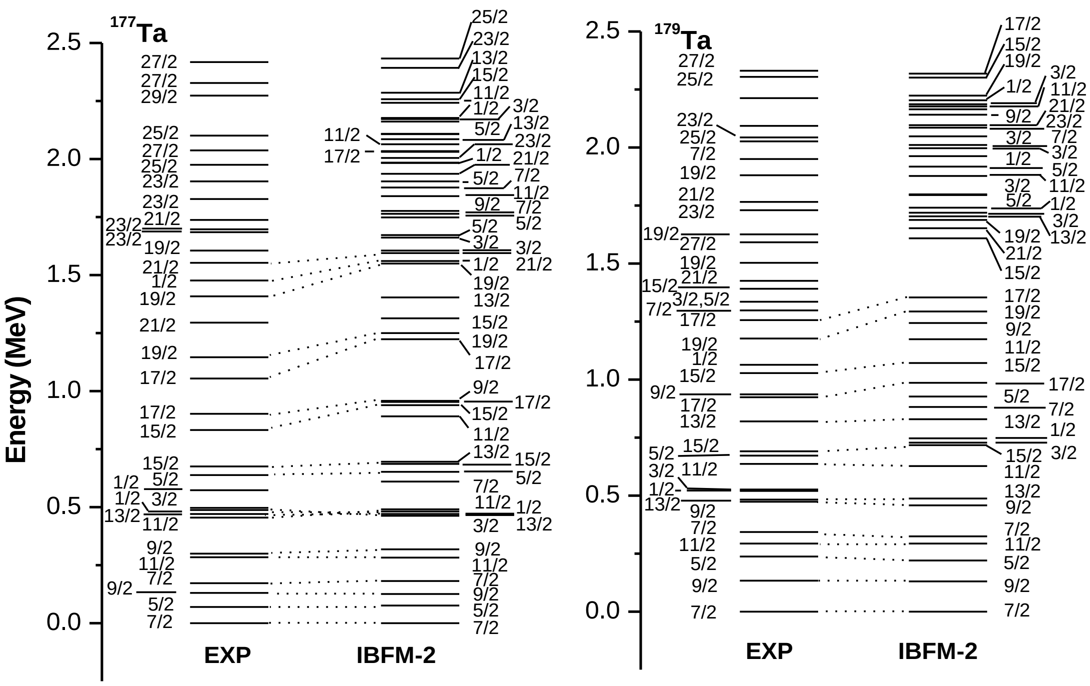

Figure 1: Comparison of levels ^{177,179}Ta isotopes predicted by IBFM-2 calculation with experimental data [37].

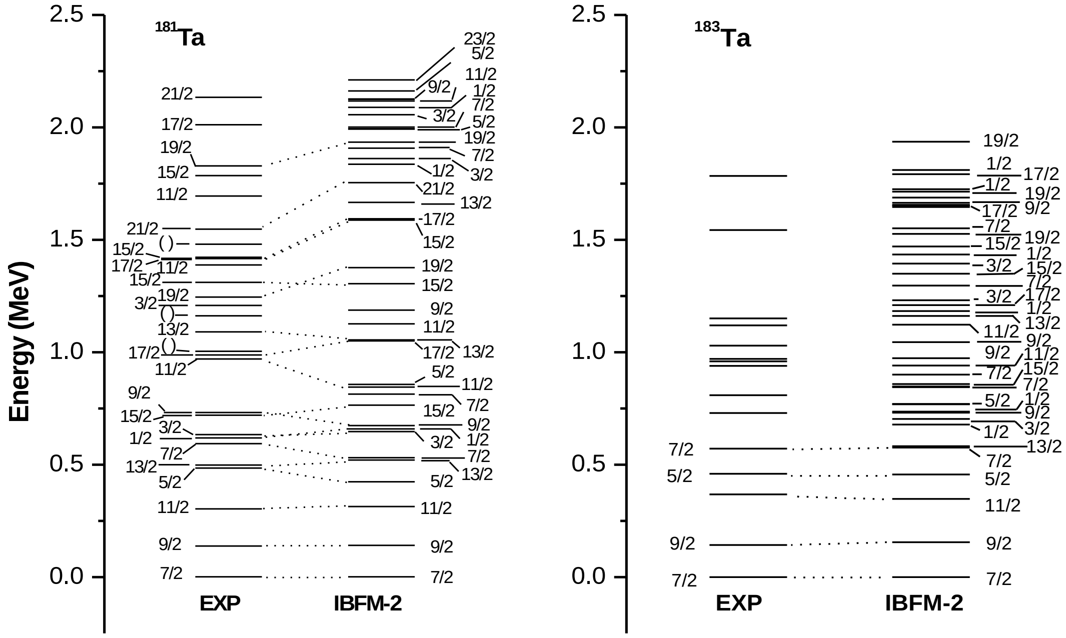

Figure 2: Comparison of levels ^{181,183}Ta isotopes predicted by IBFM-2 calculation with experimental data [37] .

Figure 2 compares the energy of the positive parity states in ^{181,183}Ta isotopes. We have succeeded in locating the low-lying states in ^{181}Ta in agreement with experiment. The calculated spectrum, a $7^+/2_3$ state appears at 0.809 MeV which has no experimental counterpart, while the calculated energy of $7^+/2_2$ state at 0..528 MeV, and this very well reproduced the experimental level at 0.590 MeV. The calculation is successful in reproducing the observed $13^+/2_1$ and $13^+/2_2$ levels, with respect to both excitation energies and single-particle orbitals. On the other hand the calculated $15^+/2_1$ state at 0.760 MeV close to experimental one at 0.716 MeV. One can note a slight increase of $9^+/2_1$ and $11^+/2_1$ energies in ^{183} Ta relative to ^{181}Ta isotope. The $7^+/2_1$ - $5^+/2_1$ energy spacing in the two isotopes agree with experimental value and very close to the $2^+{}_1$ - $0^+{}_1$ in the core nuclei. In ^{183}Ta, the calculated 0.348 MeV ($11^+/2_1$) state can be identified with the experimentally observed 0.368 MeV has not been assigned any other quantum number states. The $5^+/2_1$ state at 0.421 MeV has been identified with the 0.482 MeV state in the data. The calculated wave functions is $13\%g_{7/2}$ + 87 $\%d_{5/2}$. From figure 2, one can see that the first J^+ =

$13^+/2$ state agree very well with experiment. The IBFM-2 calculation predicted the second $J^+ = 7^+/2_1$ state at 0.528 MeV having a wave function dominated by the $\pi d_{5/2}$ orbit, and the experimental one is at 0.590 MeV.

4 -Electromagnetic transitions

In the calculation B(E2), the boson effective charges used were $e_\pi = e_\upsilon = 0.12$ *e b* and the fermion effective charge was taken as $e^F = 1.5\ e$. The boson effective charge has been obtained by adjusting the $B(E2;\ 2_1^+ \rightarrow 0_1^+)$ value for ^{182}W isotope to the experimental value and kept constant for all isotopes. The B(M1) values obtained from the model, with the *g*-factors are take to be $g_\pi = 0.5\ \mu_N$ and $g_\upsilon = 0.2\ \mu_N$, as found by fitting the reduced B(M1) for ^{181}Ta isotope. In this IBFM-2 analysis, for odd proton we $g^F_l = 1\ \mu_N$, while g^F_s factor taken as the free values quenched by a factor of $0.5 g^F_s$ = 2.97 μ_N . In most cases, such values lie in the range $g^s/\ g^{free} \approx$ 0.4 -0.7 [38-40]. The similarity in energies follows in most cases the smooth trend in B(E2) values as shown in Table 2. One can see a slow decreases of B(E2) for increasing *A*. In the model results, the E2 transition $3^+/2_1 \rightarrow 5^+/2_1$ is found to be much weaker in all isotopes. The reason for that can be understood by analysing the wave functions of the states involved. The $3^+/2_1$ state has the following main components: 66 %($2_1^+ \times d_{3/2}$)+ 27% ($2_1^+ \times s_{1/2}$) configurations. The $5^+/2_1$ state has the following main components: 89 %($2_1^+ \times d_{5/2}$)+ 11% (%($2_1^+ \times g_{7/2}$) configurations in the ^{177}Ta isotope. The decay of $7^+/2_2$ to the $5^+/2_1$ and $7^+/2_1$ state by two M1 transitions indicate different structures of the two final states. In addition to the ground-state moments, we have calculated quadrupole moment values and the magnetic moment of some excited states using the same effective charges and *g* factors. They are shown in Tables 2 and 3.

5 -Conclusion

We find that $^{177-183}$Ta are described very well by IBFM-2 with SU(3) limit Hamiltonian. It seems to be possible to reach a good description of nuclear structure of Ta isotopes by using proton single orbitals between the magic shells 50 and 80. The model predicts several states below 2 MeV, more experimental information about the level structure and electromagnetic transitions would be of great interest as a further test of the model calculation.

Table 2: Calculated and experimental [37] B(E2) (in unit $e^2\,b^2$), the quadrupole moment of ground state and low-lying states listed in last lines for $^{177-183}$Ta isotopes

$J^+_i \rightarrow J^+_f$	A=177		A=179		A=181		A=183	
	IBFM-2	EXP	IBFM-2	EXP	IBFM-2	EXP	IBFM-2	EXP
$9^+/2_1 \rightarrow 7^+/2_1$	1.9376		1.8051		1.6500	1.5807(2431)	1.4477	
$5^+/2_1 \rightarrow 7^+/2_1$	0.0828		0.0236		0.0096	0.0002	0.0065	
$11^+/2_1 \rightarrow 7^+/2_1$	0.4255		0.3826		0.3468	0.3585(729)	0.3018	
$9^+/2_2 \rightarrow 7^+/2_1$	0.0173		0.0056		0.0022		0.0017	
$7^+/2_2 \rightarrow 7^+/2_1$	0.0580		0.0165		0.0066		0.0044	
$7^+/2_2 \rightarrow 5^+/2_1$	1.9706		1.8596		1.7030		1.4758	
$7^+/2_2 \rightarrow 9^+/2_1$	0.0118		0.0042		0.0018		0.0014	
$3^+/2_1 \rightarrow 7^+/2_1$	0.0000		0.0000		0.0066		0.0000	
$3^+/2_1 \rightarrow 5^+/2_1$	0.0002		0.0002		0.0002		0.0001	
$1^+/2_1 \rightarrow 3^+/2_1$	2.2955		2.1056		1.9227		0.6587	
$1^+/2_1 \rightarrow 5^+/2_1$	0.0007		0.0006	0.0001	0.0007		0.0001	
$5^+/2_2 \rightarrow 5^+/2_1$	0.0000		0.0000		0.0000		0.0015	
$11^+/2_1 \rightarrow 9^+/2_1$	1.8900		1.7863		1.6397	1.7014(5469)	1.4422	
$13^+/2_1 \rightarrow 9^+/2_1$	0.7722		0.6944		0.6291	0.7110(1033)	0.5468	
$13^+/2_1 \rightarrow 11^+/2_1$	1.5580		1.4933		1.3778	2.2485(9115)	1.2161	
$15^+/2_1 \rightarrow 13^+/2_1$	1.2375		1.2018		1.1152	0.9297(1458)	0.9890	
$7^+/2_1$	3.4751		3.4017	3.37(4)	3.2633	3.17(2)	3.0591	
$5^+/2_1$	2.7075		2.6016		2.4833	2.35(6)	2.3090	
$3^+/2_1$	-1.5195		-1.4558		-1.3908		-0.8262	
$9^+/2_1$	1.2410		1.2791		1.2439		1.1692	
$11^+/2_1$	0.0875		0.0095		0.0366		0.0368	

Table 3 : Calculated and experimental [37] B(M1) (in unit μ_N^2), the quadrupole moment of ground state and low-lying states listed in last lines for $^{177-183}$Ta isotopes.

$J^+_i \rightarrow J^+_f$	A=177		A=179		A=181		A=183	
	IBFM-2	EXP	IBFM-2	EXP	IBFM-2	EXP	IBFM-2	EXP
$9^+/2_1 \rightarrow 7^+/2_1$	0.1309		0.1269		0.1246	0.1217(71)	0.1086	
$5^+/2_1 \rightarrow 7^+/2_1$	0.0014		0.0084		0.0141	0.00001	0.0117	
$9^+/2_2 \rightarrow 7^+/2_1$	0.0021		0.0008		0.0009		0.0006	
$7^+/2_2 \rightarrow 7^+/2_1$	0.0045		0.0010		0.0055		0.0044	
$7^+/2_2 \rightarrow 5^+/2_1$	0.3329		0.3220		0.3112		0.2823	
$3^+/2_1 \rightarrow 5^+/2_1$	0.0000		0.0000		0.0000		0.0000	
$1^+/2_1 \rightarrow 3^+/2_1$	0.0202		0.0209		0.0211		0.0298	
$5^+/2_2 \rightarrow 5^+/2_1$	0.0000		0.0000		0.0000		0.0003	
$11^+/2_1 \rightarrow 9^+/2_1$	0.2065		0.1965		0.1921	0.1664(232)	0.1678	
$13^+/2_1 \rightarrow 11^+/2_1$	0.2564		0.2400		0.2336	0.2112(375)	0.2040	
$15^+/2_1 \rightarrow 13^+/2_1$	0.2939		0.2712		0.2623	0.2541(429)	0.2302	
$7^+/2_1$	2.4516		2.4317		2.4278	2.3705(7)	2.4315	2.28(3)
$5^+/2_1$	2.5255		2.4713		2.5017		2.4999	
$3^+/2_1$	0.4864		0.4847		0.4679		0.3483	
$9^+/2_1$	2.5312		2.5040		2.5019	2.6(7)	2.5460	
$11^+/2_1$	2.6840		2.6525		2.6511		2.7303	

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التركيب النووي لنظائر التانتالوم الفردية (Ta (A=177−183

فالح حسين خضير الخضير

قسم الفيزياء / كلية التربية للعلوم الصرفة / جامعة البصرة/ البصرة / العراق

المخلص

تم حساب طاقة المستويات ذات التماثل الموجب وقيم احتمالية الانحلالات الكهرومغناطيسية لنظائر التانتالوم $^{177-183}$Ta باستخدام انموذج بوزون–فيرميون بنسخته الثانية. تم تدقيق الدوال الموجية لجميع المستويات. في فضاء الانموذج الحالي سمح للنكليون التواجد في مدارات الجسيم المنفرد الاتي $1g_{7/2}$ و $2d_{5/2}$ و $2d_{3/2}$ و $3s_{1/2}$ و $1h_{11/2}$. استخدام هاملتون التحديد الدوراني لهذا الانموذج لوصف التركيب النووي لهذه النظائر. تم تحليل قيم احتمالية الانحلالات الكهرومغناطيسية التي تعطي وصفا لطبيعة مستويات الطاقة. وجد تطابقا جيدا بين النتائج المستحصلة والقيم العملية المتوفرة

الكلمات المفتاحية: odd Ta isotopes (A=177-183), energy level, electromagnetic transitions, IBFM-2