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Low-lying spin states of even–odd ^{191}Pt nucleus

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ABSTRACT

Although the complex odd mass ^{191}Pt nucleus has been studied theoretically by several models, there is still a lack of information concerning its electromagnetic moments and transitions. The present result of an interacting boson–fermion model-1 (IBFM-1) single and multilevel calculation for positive and negative parity states of the odd mass ^{191}Pt nucleus are compared with experimental data, confirming the spin assignments for many low-lying energy states. Different core nucleus and levels have been used in this study. Electromagnetic moments based on the IBFM analysis are reported for the first time, as well as the multipolarity of transitions and mixing ratios. The present IBFM results show good agreement with the available experimental data.

Introduction

The nuclear region around A=190 is a complex region, exhibiting various kinds of shapes at very near proton or neutron closed shell nuclei. Moreover, a transition from prolate to oblate characterizes the nuclei in this region. This mass region has been studied theoretically by several models such as the particle vibration coupling model[1], the triaxial rotor-plus-particle model[2], the variable moment of inertia model[3], the particle-plus- soft rotor model[4], and interacting boson–fermion model (IBFM)[5,6]. The even–even Pt nuclei are found to lie close to a region of phase/shape coexistence and can be described without the introduction of an intruder configuration[7]. The IBM configuration mixing (IBM–CM) calculation shows that the lightest Pt isotopes are prolate deformed and finally become oblate for $^{192\text{-}194}$Pt[8]. The γ-unstable even–even core nucleus results in the emergence of well-decoupled $\nu i_{13/2}$ bands in the spectra and the presence of low-energy $11/2^{+}$ levels.

In the ^{191}Pt isotope, the negative parity states are quite complex due to two aspects: the large density of states between 0 and 1 MeV, and most of the experimental low-lying states are uncertain or have no definite spin assignment. In IBFM-2[5], which differentiates between neutrons and protons, the ^{191}Pt nucleus is characterized by coupling the odd hole neutron to the even–even core nucleus of ^{192}Pt. Only positive parity states were analyzed by assuming a single fermion occupying the $\nu i_{13/2}$ single-particle level. Energy levels are poorly reproduced in this analysis, while electromagnetic properties were omitted. In IBFM-1 analysis[6], only the negative parity states of the ^{191}Pt isotope were studied, assuming that a single fermion occupies one of the single particle orbits $2f_{5/2}, 3p_{3/2}\, and\ 3p_{1/2}$ interacts with an even–even ^{190}Pt core. Negative parity energy levels and electromagnetic transitions between some negative parity states were calculated. Although the ^{191}Pt isotope had been analyzed by IBFM-1[6] and IBFM-2[5], information concerning this nucleus is still lacking.

In this paper, the low-lying states of odd–even ^{191}Pt isotope have been studied within IBFM-1, described by coupling the odd hole neutron to the ^{192}Pt

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core nucleus for even and odd parity states. A multilevel approach was applied for negative parity states, whereas a single particle orbit $\nu i_{13/2}$ was used for calculations of positive parity states.

IBFM Energy Levels

In the IBFM, odd-A nuclei are described by the coupling of an odd fermionic quasi-particle to a collective boson core[9]. The total Hamiltonian can be written as the sum of three parts:

$$H = H_B + H_F + V_{BF} \qquad (1)$$

where H_B is the even–even core IBM Hamiltonian[10], and H_F is the fermion Hamiltonian containing only one-body terms.

Where ε_j are the quasi-particle energies, and $\hat{a}^{+}_{jm}$ $\hat{a}_{jm}$ are the creation (annihilation) operators for the quasi-particle in the Eigen state $|jm>$.

The boson–fermion interaction V_{BF}, which describes the interaction between the odd quasi-nucleon and the even–even core nucleus, is dominated by the following three terms[9]:

$$V_{BF} = \sum_j A_j [(d^{+} \times \tilde{d})^0 \times (a^{+}_j \times \tilde{a}_j)^0]^0$$

$$+ \sum_{jj'} \Gamma_{jj'} [Q^2 \times ((a^{+}_j \times \tilde{a}_j)^2]^0_0$$

$$+ \sum_{jj'j''} \Lambda^{j''}_{jj'} :[(d^{+} \times \tilde{a}_j)^{j''} \times (a^{+}_j \times \tilde{d})^{jj'}]^0_0 : \qquad (3)$$

where $\tilde{a}_{jm} = (-1)^{j-m} a_{j-m}$ and $::$ denote normal ordering whereby contributions that arise from commuting the operators are neglected. The core boson quadrupole operator[9]

$$Q^{(2)} = (s^{+} \times \tilde{d} + d^{+} \times \tilde{d})^{(2)} + \chi (d^{+} \times \tilde{d})^{(2)} \qquad (4)$$

where s, d, s^{+}, d^{+} are boson operators, and χ is a parameter shown by microscopic theory to lie through $\pm\frac{\sqrt{7}}{2}$.

The dominant terms are the second and third, which arise from the quadrupole interaction. The third term represents the exchange of the quasi-particle with one of the two fermions, forming a boson[10]. This exchange force is a consequence of the Pauli principle on the quadrupole interaction between protons and neutrons. The remaining parameters in Equation (3) are related to the Bardeen, Cooper, and Schrieffer (BCS)[11] occupation probabilities u_j, v_j of the single-particle orbits. The calculated values fo ε_j and v^2_j used in this analysis are given in Table 1.

TABLE 1. BCS parameter calculated for negative and positive ($i_{13/2}$) state occupation probabilities and quasi-particle energies.

	$1h_{9/2}$	$2f_{7/2}$	$3p_{3/2}$	$2f_{5/2}$	$3p_{1/2}$	$i_{13/2}$
ε_j (MeV)	2.15	1.91	0.885	0.922	1.29	1.12
v^2_j	0.95	0.94	0.31	0.53	0.10	0.68

The Hamiltonian of Equation (1) was diagonalized through the standard program ODDA[18] in which the IBFM parameters were identified as free parameters: A_0 = BFM, Γ_0 = BFQ, and Λ_0 = BFE, which were varied to give the best fit to the experimental excitation energies. The ^{192}Pt IBM core parameters (in MeV) PAIR=−0.083, OCT=0.0222, and ELL=0.0426 were from a previous study[12]. For negative parity states, five- and four-level calculations were conducted with the same BCS parameters in Table 1. In four-level calculations, the $1h_{9/2}$ level was considered a fully occupied level, so it was not included in the calculations. The boson–fermion parameters calculated for negative and positive parity states of ^{191}Pt are shown in Table 2 with CHI=−0.1.

TABLE 2. Hamiltonian (IBFM-1) parameters calculated for negative and positive parity of ^{191}Pt (in MeV).

	5-levels $(\pi=-)$	**4-levels** $(\pi=-)$	**1-level** $(\pi=+)$
$\Gamma_0\,(BFQ)$	**0.38**	**0.03**	**0.31**
$\Lambda_0\,(BFE)$	**0.45**	**0.51**	**0.78**
$A_0\,(BFM)$	**0.15**	**0.19**	**0.15**

Most of the experimental energy states for spin are not well established. A comparison between the present (IBFM-1) five-level calculation (

$1h_{9/2}, 2f_{7/2}, 3p_{3/2}, 2f_{5/2}$ *and* $3p_{1/2}$); Fig.1 and the reported data[13] showed good agreement for low-lying states and confirmed the spin assignment of many states. The experimental level $9/2^-$ at 100.6 KeV, which indicated $\nu h_{9/2}$ configuration[14], appeared higher at 198.5 KeV in the five-level calculation. However, it was absent in the IBFM-1[6] calculation where they chose a ^{190}Pt as a core and included the single-particle levels $3p_{3/2}, 2f_{5/2}$ *and* $3p_{1/2}$ only, as well as in the present four-level calculations. In the present IBFM-1 analysis, the inclusion of five levels in the calculation led to better agreement with the reported data than calculation with four levels. This could be attributed to the reduction in the quadrupole interaction while the exchange interaction was dominant in the case of four levels (Fig. 1).

According to the microscopic relation[15] the value κ for ^{192}Pt multiplied by the ratio $N_\nu/(N_\nu+N_\pi)$ equal to 0.26 is of the same order of magnitude as the IBFM parameter Γ_0 used in this analysis.

For a positive parity state, only $i_{13/2}$ a single level is included in this analysis. A large number of high-spin states were suggested by IBFM up to 25/2, while very few states with $j < 11/2$ were detected. It has been noticed that changing v_j^2 from 0 to 0.37 has an effect on the $J = j-1$ level causing a decrease in the energy levels. At $v_j^2 > 0.38$ the energy levels start to increase smoothly and the position of the states depends on the exchange term while it is less affected by the quadrupole term since the basis is considered as O(6). The effect on the energy of the $J = j-1$ level has also been observed in the triaxial rotor model[16] and the gamma-unstable model[17]. Only a few positive parity states were compared with available experimental data and shown in Fig. 1. A good agreement between experimental energy levels and IBFM results is achieved.

A quantitative estimate of the quality of fits can be obtained by computing the average percentage deviation Φ between experiment and theory which is defined by

$$\Phi = \frac{\sum |\exp. - calc.|}{\sum |\exp.|}\% \qquad (5)$$

Where the sums run over all fitted quantities. Φ values found to be 27.6% for negative parity states and 14.4% for positive parity states.

Transition probabilities and Electromagnetic moments

Any nuclear model wave functions may test from its electromagnetic transitions and moment calculations.

Two terms constructed the electromagnetic transition operators, the first of which acts only on the boson part of the wave function, and the second acts only on the fermion part in equation (1).

In the IBFM the E2 operator is[15]

$$T^{(E2)} = e_B Q^{(2)} + e_F \sum Q_{jj'} (a_j \times \tilde{a}_{j'})^2 \qquad (6)$$

Where e_B and e_F are the boson and fermion effective charges. The M1 operator is[15]

$$T^{(M1)} = \sqrt{30/4\pi}\, g_B (d^+ \times \tilde{d})^{(1)} - \sum_{jj'} g_{jj'} [j(j+1)(2j+1)/4\pi]^{1/2} (a_j^+ \times \tilde{a}_{j'})^{(1)} \qquad (7)$$

Where g_B is the even-even core boson g-factor, and $g_{jj'}$ is the single particle contribution which depends on g_ℓ and g_s (orbital and spin g-factor) of the odd nucleon.

The transition strengths B(E/Mλ) between levels with spin J and J' are obtained from the operators of equations (5 and 6) as

$$B(E/M\lambda; J \rightarrow J') = \frac{\left| \left\langle J' \left\| T^{(E/M\lambda)} \right\| J \right\rangle \right|^2}{(2J+1)} \qquad (8)$$

The wave functions obtained by the computer code ODDA have been used by the code PBEM to calculate the electric and magnetic transition strength. The complete range of $T^{(M1)}$ and $T^{(E2)}$ obtained

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by PBEM using the following effective boson and fermion charges and g- factors for both positive and negative parity states:

$$e_B = 0{,}132\ \ eb,\ e_F = -0.132\ \ eb,\ g_\ell = 0\ ,\ g_d = 0.27\ \ n.m.$$
$$and\ \ g_s = -3.826\times 0.4 = -1.5304\ \ n.m.$$

The E2/M1 mixing ratios (δ) can be easily calculated using the relation

$$\delta(E2/M1) = 0.835\ E_\gamma(MeV)\ \frac{\langle J_f \| T^{(E2)} \| J_i \rangle}{\langle J_f \| T^{(M1)} \| J_i \rangle} \qquad (9$$

Multipolarity and mixing ratios for some transitions were calculated from five-level results and compared with available experimental data shown in Table 3. In general, good agreement was observed between IBFM results and reported data.

TABLE 3. Present IBFM multipolarity and mixing ratios (δ) calculated compared with experimental results for some transitions for ^{191}Pt.

$2(J_i^\pi \to J_f^\pi)$	$M(\gamma)$		$(\delta)\ (eb/\mu_N)$	
	IBFM	**Experimental**	**IBFM**	**Experimental**
$5_1^- \to 3_1^-$	**E2 (0.004)**			
$1_1^- \to 3_1^-$	**M1+E2**	**M1+E2**	**0.036**	**0.034(9)**
$9_1^- \to 5_1^-$	**E2 (0.28)**	**E2 (0.15)**		
$3_2^- \to 3_1^-$	**M1+E2**	**M1+E2**	**0.49**	**0.55(9)**
$5_2^- \to 1_1^-$	**E2 (0.032)**	**M1+E2**		**0.40(4)**
$5_2^- \to 5_1^-$	**M1+E2**		**0.88**	
$7_2^- \to 5_1^-$	**M1+E2**	**M1+E2**	**1.2**	**0.62(12)**
$7_2^- \to 3_1^-$	**E2 (0.032)**	**E2**		
$5_3^- \to 5_1^-$	**M1+E2**	**M1+E2**	**0.41**	**0.30(10)**
$11_1^- \to 13_1^-$	**M1+E2**	**M1+E2**	**0.10**	**0.154(22)**
$9_1^- \to 11_1^-$	**M1+E2**	**M1+E2**	**0.33**	**0.33(3)**
$9_1^- \to 13_1^-$	**E2 (0.013)**			

From the matrix elements of $T^{(M1)}$ and $T^{(E2)}$ the magnetic dipole moments (μ_J) and the electric quadrupole moment (Q_J) for a state with spin j can be obtained as[15]:

$$\mu_J = \sqrt{\frac{4\pi}{3}}\sqrt{\frac{J}{(2J+1)(J+1)}}\ \langle J \| T^{(M1)} \| J \rangle \qquad (10)$$

$$Q_J = \sqrt{\frac{16\pi}{5}}\sqrt{\frac{J(2J-1)}{(2J+1)(J+1)(2J+3)}}\ \langle J \| T^{(E2)} \| J \rangle \qquad (11)$$

Both magnetic dipole and electric quadrupole moments calculated using 5-levels results of the ground state agrees very well with experimental reported[18] as shown in Table 4 while 4-levels show poor agreement. Experimentally, the measured quadrupole moment of ^{191}Pt ground state is negative. Both, mixing of different quasi-particle configuration at triaxial shape and certain configurations at prolate shape can produce a negative quadrupole moment[18]. In previous IBFM calculations[5,6] there is no result concerning the moments calculation.

TABLE 4. Calculated moments for some states of the ^{191}Pt nucleus.

$2J^\pi$	$Q(b)$		$\mu(nm)$	
	IBFM	**Exp.**	**IBFM**	**Exp.**
3_1^-	**- 0.84**	**-0.86(11)[19] -0.98(5)[20] -0.64(26)[21,22] - 0.87(4)[23]**	**0.51**	**0.494(8)[19] 0.501(5)[20] 0.500(10)[21,22] 0.492(10)[23]**
5_1^-	**0.60**		**0.26**	
1_1^-			**0.22**	
9_1^-	**1.7**		**0.23**	
3_2^-	**0.69**		**0.46**	

13_1^+	**0.72**		**1.31**	
11_1^+	**1.41**		**1.30**	
9_1^+	**1.11**		**1.24**	

The present calculation showed good agreement with experimental energy levels, electromagnetic moments, and mixing ratios. The ^{191}Pt nucleus described as a hole coupled to ^{192}Pt core yielded better results than a particle coupled to the ^{190}Pt core because the bosons are hole-like.

Conclusions

In this paper, an analysis of nucleus ^{191}Pt was carried out based on IBFM-1 using ^{192}Pt as a core. Although this nucleus was described by IBFM-1 and IBFM-2, in this work, the result was more realistic than the others. The use of ^{192}Pt as a core was found to be more reliable than the ^{190}Pt core. Spin assignments for many low-lying negative parity states were confirmed in this work. In positive parity states, the effect of $J = j - 1$ on the energy of the states was observed to be dependent on the exchange strength. The present calculation was in good agreement with the experimental data.

Calculations of electromagnetic moments based on the IBFM were carried out for the first time for the odd mass nucleus ^{191}Pt, and they are sensitive to multilevel calculations.

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مستويات البرم المنخفضة للنواة الفردية–الزوجية ^{191}Pt

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الخلاصة:

على الرغم من دراسة النواة الفردية المعقدة من قبل عدة انظمة نووية الا انه لا زال هنالك نقص في العزوم الكهرومغناطيسية وانتقالاتها. نتائج الدراسة الحالية باستخدام نظام تفاعل البوزن–فرميون (1) باستخدام مستوي واحد وعدة مستويات لكلا التماثلين الفردي والزوجي قورنت مع النتائج التجريبية المتوفرة وتم تاكيد برم عدة مستويات طاقة. تم استخدام في هذه الدراسة نواة اساسية ومستويات تفاعل مختلفة عن الدراسات السابقة. نتائج نظام تفاعل البوزن– فرميون (1) الحالية للعزوم الكهرومغناطيسية تم الحصول عليها لأول مرة بالإضافة الى التحولات التعددية القطبية ونسب اختلاطها. نتائج نظام تفاعل البوزن– فرميون (1) الحالية اظهرت توافق مع النتائج العملية المتوفرة.

الكلمات المفتاحية: التركيب النووي، نظام تفاعل البوزن– فرميون، مستويات الطاقة، الانتقالات الكهرومغناطيسية. نواة البلاتينيوم.

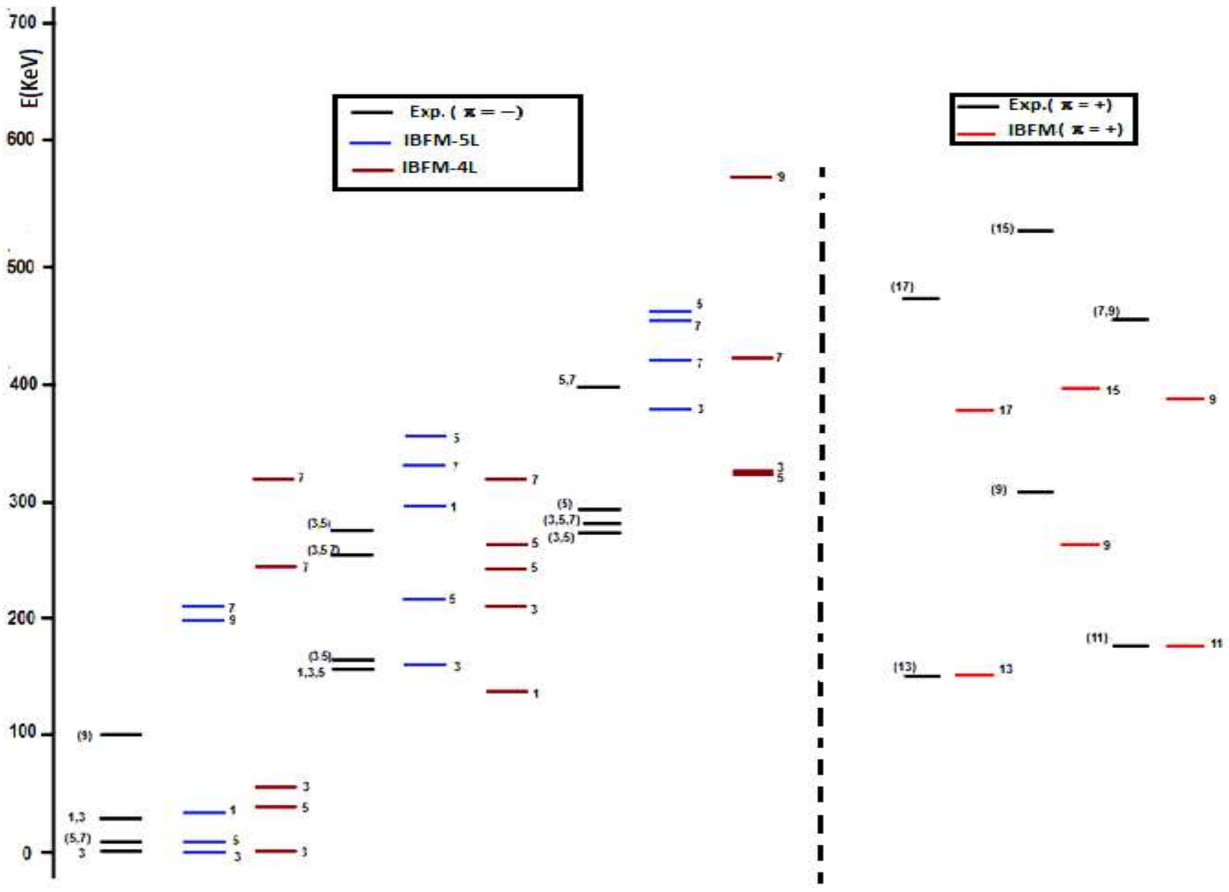

FIG. 1. (Color online) Comparison of the energy levels in ^{191}Pt with IBFM calculations. The levels with "( )" indicate that the spin of the states are uncertain. Spin values are shown multiplied by two.