

$d_{5/2}^3$ — AND $s_{1/2} d_{3/2} g_{7/2}$ — PARAMETRIZATION FOR ^{101}Mo IN
IBFM/PTQM AND THE ELECTROMAGNETIC PROPERTIES
OF ANOMALOUS TRIPLET

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The possibilities to describe the anomalous low-lying triplet of ^{101}Mo have been investigated in the boson-fermion model IBFM/PTQM. Two possible classifications of triplet states, associated with $\tilde{d}_{5/2}$, $\tilde{d}_{5/2}$, $\tilde{d}_{5/2}$ and $\tilde{s}_{1/2}$, $\tilde{d}_{3/2}$, $\tilde{g}_{7/2}$ quasi-particle states, respectively, have been studied in light of the electromagnetic properties of anomalous triplet states.

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1. Introduction

The nucleus ^{101}Mo appears at the onset of the region of deformation around $A = 100$. On one side, the $N = 56$ even-even isotones exhibit a vibrational-like character, while the $N = 60$ nuclei exhibit deformation in the ground state. In the chain of Mo isotopes, ^{101}Mo is situated between ^{99}Mo with a single-particle character and ^{103}Mo with a rotational ground state band. Therefore, the structure of ^{101}Mo is of particular interest.

A pronounced pattern of ^{101}Mo is the appearance of the low-lying triplet of states with $J^\pi = 1/2^+$ (g. s), $(3/2^+, 5/2^+)$ at 14 keV and $(3/2^+, 5/2^+)$ at 57 keV¹⁾.

There are three pronounced experimentally observed electromagnetic intensity rules for these states:

$$\frac{I_\gamma(57 \rightarrow 0)}{I_\gamma(57 \rightarrow 14)} \approx 0; \quad (1a)$$

$$(48)\% E2 \text{ admixture in the } 57 \rightarrow 14 \text{ keV transition}; \quad (1b)$$

$$14 \rightarrow 0 \text{ keV } M1 \text{ transition is strongly hindered.} \quad (1c)$$

We have theoretically investigated the structure of ^{101}Mo in the framework of SU(6) symmetry by coupling a neutron quasiparticle in the $N = 50$ –82 shell to the ^{100}Mo core. The even-even core nucleus ^{100}Mo is described in the interacting boson model IBM²⁾/TQM^{3,4)} and the odd-even nucleus ^{101}Mo in the interacting boson-fermion model IBFM⁵⁾/PTQM^{4,6)}. We have performed the calculations for ^{101}Mo employing the TQM representation of IBM, with the Hamiltonian given by Eqs. (3) and (9–13) of Ref. 6.

2. IBFM/PTQM calculation for $s_{1/2} d_{3/2} g_{7/2}$ — parametrization

Having in mind the ambiguity in the spin of the 57 keV-level, we shall first consider the case with $3/2^+$ spin/parity assignment for this level.

It is rather difficult to accommodate for the intensity rules (1a–c) in the presence of s and d orbitals. A possibility to account for these properties in the leading-order approximation of IBFM/PTQM is to associate the 57, 13.5 and 0 keV levels with components involving $\tilde{g}_{7/2}$, $\tilde{d}_{3/2}$ and $\tilde{s}_{1/2}$ quasiparticles, respectively. For an appropriate parametrization this leading-order result should be preserved in the presence of IBFM correlations. In this sense the parametrization was determined in the present calculation. The IBM/TQM core parameters are $h_1 = 0.234$, $h_2 = 0.135$, $h_3 = 0.177$, $h_{40} = -0.053$, $h_{42} = -0.100$, $h_{44} = 0.255$ with the boson number $N = 6$. This parametrization globally accounts for the experimental levels in ^{100}Mo core. However, it should be noted that two different structures coexist in ^{100}Mo , one closer to the 0(6), and the other to the SU(5) limit⁷⁾. Therefore, the IBM-1 description, employed in this paper, is an approximation intended to simulate an effective core. The IBFM/PTQM parameters are chosen as follows.

The $\tilde{s}_{1/2}$, $\tilde{d}_{5/2}$, $\tilde{d}_{3/2}$, $\tilde{g}_{7/2}$ quasiparticle energies and occupation probabilities are 0, 0.24, 0.45, 1.55 and 0.5, 0.5, 0.61, 0.16, respectively. We note that the available experimental information on the spectroscopic factors in ^{101}Mo indicates the possibility of having $s_{1/2}$, $d_{5/2}$ and $d_{3/2}$ configurations nearly half-filled^{8,9)}. The boson-fermion interaction strengths are $A_0 = 0.04$, $\Gamma_0 = 1.02$, $\chi = -\frac{\sqrt{7}}{2}$. This parametrization will be referred to as parametrization I.

The low-lying positive-parity spectrum of ^{101}Mo , calculated using this parametrization, is presented in Fig. 1 and compared to the available experimental levels. Accordingly we attribute the $3/2^+$ assignment to the 57 keV level. The calculated wave functions of the 0_1 and 2_1 states of the boson core are presented in Table 1 and the IBFM/PTQM wave functions of the three lowest-lying states of ^{101}Mo in Table 2.

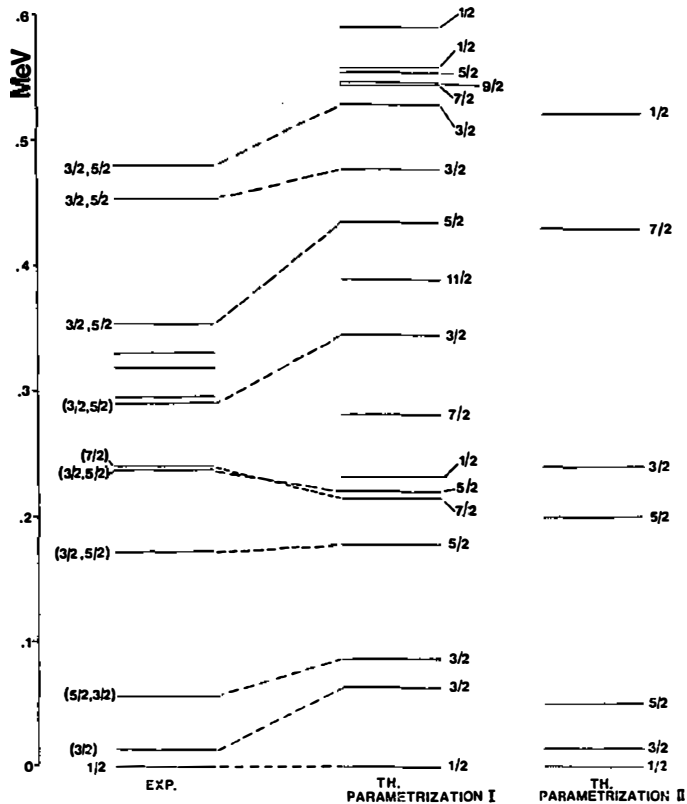


Fig. 1. Calculated low-lying positive-parity levels of ^{101}Mo (parametrization I) in comparison to experimental levels¹⁾. In the last column the calculated low-lying positive-parity levels associated with the parametrization II are presented. Calculated states are tentatively assigned to the experimental levels.

TABLE 1.

| $n_d I$ | $\xi_{n_d I}^{0_1}$ | $n_d I$ | $\xi_{n_d I}^{2_1}$ |
|---------|---------------------|---------|---------------------|
| 00 | 0.56 | 12 | 0.64 |
| 20 | 0.68 | 22 | -0.15 |
| 30 | 0.21 | 32 | 0.65 |
| 40 | 0.39 | 42 | -0.21 |
| 50 | 0.17 | 42' | -0.18 |
| 60 | 0.06 | 52 | 0.25 |
| 60' | 0.03 | 52' | 0.05 |
| | | 62 | -0.08 |
| | | 62' | -0.09 |

Wave functions are expressed in the sd -boson basis

$$|I\rangle = \sum_{n_d v} \xi_{n_d v}^I |n_d v I\rangle.$$

Here, $|n_d v I\rangle$ denotes the state with n_d d -bosons, coupled to the angular momentum I , and with $N-n_d$ s -bosons. The quantum number v is an additional quantum number to distinguish, if needed, between different states of the same n_d and I .

We employ the following notation for the basis states: $|n_d I\rangle$ denotes the boson state $|n_d v_{lowest} I\rangle$ (the quantum number v is not needed for $n_d < 4$). Otherwise we abbreviate $|n_d v' I\rangle$ by $|n_d I'\rangle$, where $v' > v_{lowest}$.

Wave functions of the 0_1 and 2_1 states of the boson core.

Employing the IBFM/PTQM wave functions we have calculated the electromagnetic properties of the low-lying states. The values of the effective charges and gyromagnetic ratios are $e^{s,p} = 0.5$, $e^{vib} = 4$, $g_R = 0.4 \frac{Z}{A}$, $g_I = g_I^{free} = 0$, $g_s = 0.7 g_s^{free}$, $g_T = \frac{1}{100} g_T^{free}$, $\langle r^2 \rangle = -0.72$. Here $e^{s,p}$, g_I , g_s have the standard values and the strength g_T of the tensor term is in accordance with Ref. 10. The g_R value is reduced from its bare value, similarly as in Ref. 6. The effective boson charge e^{vib} was adjusted to the experimental data. We note that throughout the nuclear systematics the range of values for e^{vib} is usually between 2 and 4.

Employing this parametrization we get the calculated half-lives of the low-lying states presented in Table 3. This calculation gives

$$\frac{I_\gamma(3/2_2 \rightarrow 1/2_1)}{I_\gamma(3/2_2 \rightarrow 3/2_1)} = 0.10$$

which is in reasonable agreement with the rule (1a). We note that even further decrease of this value could be obtained by introducing the $\Delta N = 2$ term in $E2$ operator, along the line as in Refs. 11 and 12.

TABLE 2.

| $j, n_d I$ | $\xi_{j, n_d I}^{1/2}$ | $j, n_d I$ | $\xi_{j, n_d I}^{3/2_1}$ | $j, n_d I$ | $3/2_2$ $j, n_d I$ |
|---------------|------------------------|---------------|--------------------------|----------------|-----------------------|
| $s_{1/2}, 00$ | 0.47 | $s_{1/2}, 22$ | 0.10 | $s_{1/2}, 12$ | 0.14 |
| $s_{1/2}, 20$ | 0.65 | $s_{1/2}, 32$ | 0.14 | $s_{1/2}, 32$ | 0.15 |
| $s_{1/2}, 30$ | 0.23 | $d_{3/2}, 00$ | 0.35 | $s_{1/2}, 42$ | -0.11 |
| $s_{1/2}, 40$ | 0.40 | $d_{3/2}, 20$ | 0.56 | $d_{3/2}, 12$ | -0.19 |
| $s_{1/2}, 50$ | 0.21 | $d_{3/2}, 22$ | 0.13 | $d_{3/2}, 32$ | -0.23 |
| $d_{3/2}, 22$ | -0.15 | $d_{3/2}, 30$ | 0.30 | $d_{3/2}, 40$ | -0.23 |
| $d_{3/2}, 32$ | -0.11 | $d_{3/2}, 40$ | 0.31 | $d_{3/2}, 42$ | 0.14 |
| $d_{3/2}, 42$ | -0.13 | $d_{3/2}, 42$ | 0.13 | $d_{3/2}, 42'$ | 0.13 |
| | | $d_{3/2}, 50$ | 0.26 | $d_{3/2}, 50$ | -0.14 |
| | | $g_{7/2}, 22$ | 0.14 | $d_{5/2}, 32$ | 0.11 |
| | | $g_{7/2}, 32$ | 0.27 | $g_{7/2}, 12$ | 0.29 |
| | | $g_{7/2}, 52$ | 0.23 | $g_{7/2}, 22$ | -0.16 |
| | | $g_{7/2}, 62$ | -0.11 | $g_{7/2}, 24$ | -0.12 |
| | | | | $g_{7/2}, 32$ | 0.40 |
| | | | | $g_{7/2}, 33$ | -0.10 |
| | | | | $g_{7/2}, 42$ | -0.37 |
| | | | | $g_{7/2}, 42'$ | -0.29 |
| | | | | $g_{7/2}, 44$ | -0.26 |
| | | | | $g_{7/2}, 52$ | 0.19 |
| | | | | $g_{7/2}, 54$ | 0.15 |
| | | | | $g_{7/2}, 54'$ | -0.12 |

Wave functions are expressed in the boson-fermion coupled basis

$$|J\rangle = \sum_{j, n_d, I} \xi_{j, n_d, I}^J |j, n_d, v; J\rangle.$$

In the basis state $|j, n_d, v, I; J\rangle$ the quasiparticle $|j\rangle$ and the n_d -boson state $|n_d, v, I\rangle$ are coupled to the total angular momentum J . For notation of boson states see caption to Table 1.

Only components with the amplitudes larger than 1% are listed.

Wave functions of the $1/2_1$, $3/2_1$ and $3/2_2$ states in ^{101}Mo .

TABLE 3.

| Level (keV) | $T_{1/2}^{th}$ | $T_{1/2}^{exp}$ |
|-------------|--------------------|--------------------------|
| 13.5 | 0.20 μs | 0.222 (10) μs |
| 57.0 | 0.17 μs | 0.124 (10) μs |
| 171.0 | 0.02 ns | |
| 237.6 | 0.10 ns | |
| 289.6 | 0.35 ns | 0.16 ns |

Calculated halfives of several low-lying states in ^{101}Mo and comparison to the available data. The attribution of levels is according to the second column of Fig. 1.

On the other hand due to enhanced $3/2_2 \rightarrow 3/2_1$ $E2$ -transition ($B(E2; 3/2_2 \rightarrow 3/2_1) = 0.021 e^2 b^2$) and hindered $M1$ -transition ($B(M1; 3/2_2 \rightarrow 3/2_1) = 0.0003 \mu_N^2$) we get sizeable $E2$ admixture in the $3/2_2 \rightarrow 3/2_1$ transition, amounting to 38%, in agreement with the experimental value (1b).

Both the $M1$ transitions among the triplet states, $3/2_2 \rightarrow 1/2_1$ and $3/2_2 \rightarrow 3/2_1$ are sizeably hindered. This is due to the Δl -forbiddness of transitions among the main components; this forbiddness is approximately preserved in the presence of boson-fermion interaction¹⁰⁾.

The low-lying states of ^{101}Mo exhibit a transitional character. This can be seen from the structure of the wave functions of the triplet states (see Table 2) in comparison with the structure of the wave functions of the 0_1 , 2_1 states in the corresponding boson core (see Table 1). Let us first compare the wave function of the ground state of the boson core with the characteristics of the wave functions associated with three dynamical symmetries of IBM/TQM. In the $SU(5)$ limit the $|0_1\rangle$ state is based on the $|n_d I\rangle = |00\rangle$ component; on the other hand, in the $SU(3)$ limit the $|0_1\rangle$ state is characterized by a superposition of all available boson states¹³⁾ with total angular momentum zero and the largest amplitudes appear for the components having the number of d -boson $n_d \approx \frac{2N}{3} = 4^4$. As seen from Table 1, the structure of $|0_1\rangle$ wave function of the boson core is between these limiting cases. Furthermore, the $|0_1\rangle$ wave function exhibits also some signature effect: the components with even number of d -bosons are larger than those with odd number. Similarly, in the $|2_1\rangle$ wave function the components with odd number of d -bosons are larger than those with even. Such signature effects characterize the $0(6)$ limit. These features reveal a complex structure of the boson core, with the wave functions exhibiting the mixture of characteristics of three limiting symmetries.

In the IBFM wave functions we can group the components into blocks which approximately resemble the n_d -structure of the boson core. For example, the first five components in the $|1/2_1\rangle$ wave function from Table 2 can be approximately grouped into a block

$$0.47 \tilde{[s_{1/2}, 00; 1/2\rangle} + 0.65 \tilde{[s_{1/2}, 20; 1/2\rangle} + 0.23 \tilde{[s_{1/2}, 30; 1/2\rangle} + \\ + 0.40 \tilde{[s_{1/2}, 40; 1/2\rangle} + 0.21 \tilde{[s_{1/2}, 50; 1/2\rangle} \approx 0.9 \tilde{[s_{1/2}, 0_1; 1/2\rangle}.$$

On the r. h. s. 0_1 denotes the wave function of the ground state of the boson core which is given in Table 1. Similarly, it is seen that the $3/2_1$ and $3/2_2$ states are characterized by leading blocks $\tilde{[d_{3/2}, 0_1; 3/2\rangle}$ and $\tilde{[g_{7/2}, 2_1; 3/2\rangle}$, respectively. These blocks correspond to truncated weak coupling (TWC) basis from Ref. 14. Therefore, we clearly see that the low-lying states of ^{101}Mo do not exhibit the rotational ($SU(3)$) character, but the transitional one which can be viewed as a combination of the Hamiltonian terms corresponding to three limiting symmetries.

The nature of the low-lying triplet states is reflected in the calculated static moments. Present IBFM calculation gives $Q(3/2_1) = 0.35 eb$, $Q(3/2_2) = -1.11 eb$. The signs reflect the hole-like character of $\tilde{d}_{3/2}$ and the particle-like character of $\tilde{g}_{7/2}$ quasiparticle states ($\text{sign } Q(\tilde{j}) = \text{sign } \{v_j^2 - u_j^2\}$), and the magnitudes which

are sizeably enhanced over the single-particle values reflect the collectivity of the boson-fermion system. The calculated magnetic dipole moments $\mu(1/2_1) = -1.22\mu_N$, $\mu(3/2_1) = 0.86\mu_N$ and $\mu(3/2_2) = 0.68\mu_N$ reflect the signs associated with $s_{1/2}$, $\tilde{d}_{3/2}$ and $g_{7/2}$ single particle configurations, respectively. These leading order sign predictions are preserved by the leading-order boson-fermion interaction due to the mechanism similar to the one investigated in Ref. 10.

3. IBFM/PTQM calculation for $d_{3/2}$ — parametrization

Let us now investigate the case if the 57-keV state is assigned $5/2^+$ spin/parity assignment. Here we consider the parametrization when the low-lying triplet is interpreted as the IBFM anomalous triplet of states $J = j = \frac{5}{2}$, $J = j - 1 = \frac{3}{2}$, $J = j - 2 = \frac{1}{2}$, associated with $d_{5/2}$ quasiparticle. The calculation of such a type was attempted, using the quasiparticle energies and boson-fermion interaction strengths similar to those from the calculations for heavier $N = 59$ isotones ^{103}Pd and ^{103}Ru (Refs. 15—17) with the lowest-lying $\tilde{d}_{5/2}$ quasiparticle state. The parametrization along this line, referred to as parametrization II, is as follows. The boson core parameters, adjusted to the positions of the low-lying group of states 2_1^+ , 0_2^+ , 2_2^+ , 4_1^+ , (2_3^+) , (3_1^+) (similar to Ref. 18) are: $h_1 = 0.56$, $h_2 = -0.086$, $h_3 = 0.1$, $h_{40} = -0.2$, $h_{42} = -0.195$, $h_{44} = 0.18$, $N = 6$. The quasiparticle states $\tilde{d}_{5/2}$, $g_{7/2}$, $s_{1/2}$, $\tilde{d}_{3/2}$ have the energies 0, 0.75 MeV, 1 MeV, 1.5 MeV and the occupation probabilities 0.6, 0.2, 0.05, 0.05, respectively. The fermion-boson interaction strengths are $A_0 = 0.15$, $\Gamma_0 = 0.6$, $A_0 = 5.25$, $\chi = -\frac{7}{2}$.

The energy spectrum obtained by the calculation in the parametrization II is presented on the r. h. s. of Fig. 1.

In this case the low-lying triplet states of ^{101}Mo would be associated with the $1/2_1$, $3/2_1$, $5/2_1$ model states. These model states have the largest components $|\tilde{d}_{5/2}, 12; 1/2\rangle$, $|d_{5/2}, 5/2; 3/2\rangle$ and $|\tilde{d}_{5/2}, 00; 5/2\rangle$, respectively, with small admixtures arising from other single-particle states. Such a pattern, referred to as $J = j - 1$, $j - 2$ anomaly, was previously studied in the frame of IBFM and of the cluster-vibration model^{5, 19, 20}.

The electromagnetic properties associated with the IBFM parametrization II are as follows. Employing the effective charges from the ^{103}Ru calculation¹⁶ and standard gyromagnetic ratios ($g_R = \frac{Z}{A}$, $g_l = g_l^{free} = 0$, $g_s = 0.7 g_s^{free}$) for the $3/2_1 \rightarrow 1/2_1$ transition we get $B(E2; 3/2_1 \rightarrow 1/2_1) = 0.0028 e^2 b^2$, $B(M1; 3/2_1 \rightarrow 1/2_1) = 0.0034 \mu_N^2$, giving $T_{1/2}(3/2_1) = 0.34 \mu\text{s}$, in rather good agreement with experiment. These results are similar to the ones obtained in the parametrization I: $B(E2; 3/2_1 \rightarrow 1/2_1) = 0.091 e^2 b^2$, $B(M1; 3/2_1 \rightarrow 1/2_1) = 0.0032 \mu_N^2$. However, for depopulation of the second excited state the situation is quite different for the parametrizations I and II. The results of the parametrization II are: $B(E2; 5/2_1 \rightarrow 3/2_1) = 0.0001 e^2 b^2$, $B(E2; 5/2_1 \rightarrow 1/2_1) = 0.047 e^2 b^2$, $B(M1; 5/2_1 \rightarrow$

$\rightarrow 3/2_1) = 0.0007 \mu_N^2$. Therefrom, the theoretical predictions of the parametrization II associated with the intensity rules (1a—c) are:

$$\frac{I_\gamma(57 \rightarrow 0)}{I_\gamma(57 \rightarrow 13.5)} = 0.34.$$

The $57 \rightarrow 13.5$ keV transition contains only 0.1% $E2$ admixture, and $13.5 \rightarrow 0$ keV $M1$ transition is strongly hindered. The very small calculated $E2$ admixture in the $57 \rightarrow 13.5$ keV transition is in strong contradiction to the experiment (1b). This discrepancy is a persistent feature, rather insensitive to details of parametrization associated with dominant role of $d_{5/2}$ configuration. Thus, the electromagnetic properties of the low-lying triplet states exclude the possibility to associate the three lowest-lying states with the $I = j, j - 1, j - 2$ anomalous triplet.

4. Conclusions

We have investigated two possible sets of parameters for the IBFM/PTQM calculation of ^{101}Mo , in light of the electromagnetic properties of the low-lying anomalous triplet, which enforce rather stringent conditions on theoretical interpretations. It was shown that the $I = j, j - 1, j - 2$ interpretation of triplet states, associated with $j = \tilde{d}_{5/2}$, leads to inconsistency with the electromagnetic data. On the other hand, the attribution of three triplet states to $\tilde{s}_{1/2}$, $\tilde{d}_{3/2}$ and $\tilde{g}_{7/2}$ quasiparticle configurations, respectively, provides a framework for qualitative accommodation of electromagnetic data.

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$d_{5/2}^2$ — i $s_{1/2} d_{3/2} g_{7/2}$ — PARAMETRIZACIJA ZA ^{101}Mo U IBFM/PTQM I
ELEKTROMAGNETSKA SVOJSTVA ANOMALNOG TRIPLETA

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Istraživane su mogućnosti opisa anomalnog niskoležećeg tripleta u ^{101}Mo u bozonsko-fermionskom modelu IBFM/PTQM. Razmatrane su dvije moguće klasifikacije tripletnih stanja, pridružene kvazičestičnim stanjima $\tilde{d}_{5/2}$, $\tilde{d}_{5/2}$, $\tilde{d}_{5/2}$ i $\tilde{s}_{1/2}$, $\tilde{d}_{3/2}$, $\tilde{g}_{7/2}$, uzevši u obzir elektromagnetska svojstva tih stanja.