第28卷 第4期
2004年4月

高 能 物 理 与 核 物 理
HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS

Vol.28, No.4
Apr., 2004

Isospin and Mixed Symmetry Excitations in $^{60-66}$Zn Isotopes*

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Abstract The level structure of $^{60-66}$Zn isotopes is studied within the framework of interacting boson model-3 (IBM-3). The mixed symmetry states are investigated in these nuclei by analyzing the wave functions. The isospin excitation states are identified for ^{60}Zn ($N=Z$) nucleus. The calculated energy levels and transition probabilities are compared with available experimental data. The results obtained and the values of parameters used in this calculation indicated that the Zn isotopes are in the transition from vibrational to γ-unstable nuclei.

Key words IBM-3, isospin, mixed symmetry states, $^{60-66}$Zn isotopes

1 Introduction

The symmetry concept has been very productive in investigating nuclear structure and provides a simple interpretation of excitation energies. This concept has been used in the interacting boson model. First introduced by Arima and Iachello[1-3], nuclear properties are described in terms of pairs of nucleons paired to angular momentum $L=0$ (s-boson) and $L=2$ (d-boson). The six possible boson states are classified according to the irreducible representation $[N]$ of the group $U(6)$ and its subgroups. In its original version (IBM-1), only one kind of boson is considered. In IBM-2, a relation among the IBM and the underlying shell model has been established by including the proton and neutron degree of freedom[4]. In lighter nuclei the valence protons and neutrons are filling the same major shell, isospin must be introduced. Within the IBM with isospin (IBM-3)[5], the neutron-proton pair must be included in addition to the two other types of bosons in the IBM-2 to form an isospin triplet.

There have been intensive interests in the collective motions in the medium and light nuclei[6-8]. Even-even Zn nuclei have been the subject of extensive experimental and the oretical investigations[9-14]. A number of studies[15-17] have explored the structure of these nuclei and it has been shown that their structure cannot be explained by the simple vibrational mode. It is therefore interesting to carry out a systematic comparison of the experimental data with IBM-3 model calculations. In a recent work[18] we have studied the ^{48,50}Cr isotopes in the framework of IBM-3. This study provides information on the mixed symmetry states and isospin excitation ($T>T_z$), as well as electromagnetic transitions. A good agreement with available experimental data has been obtained. We will extend the analysis to the Zn isotopes in this work. The aim of the present work, is to carry out a systematic IBM-3 calculations of the even-even Zn nuclei with $A=60$—66. Special attention will be given to the identification of isospin and symmetric structure in the low-lying energy levels.

2 The IBM-3 hamiltonian

The microscopic picture of the interacting boson model is given in terms of collective pairs of nucleon. The

Received 4 August 2003

* Supported by NSFC (10047001), Major State Basic Research Development Program (G200077400)

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building blocks of the IBM-3 are the neutron-neutron boson (s_ν, d_ν), neutron-proton boson (s_δ, d_δ) and proton-proton boson (s_π, d_π). The three s-bosons and three d-bosons form a $T = 1$ multiplet, respectively. The IBM-3 has $U(18)$ group as its dynamical symmetry group, and the dynamical group chain must contain the $O_L(3)$ and $SU_T(2)$ groups, because the angular momentum and the isospin are good quantum numbers[19—21]. One class of group chain is the $U(6) \times U(3)$ limit, which includes[22]

$$\begin{aligned}
&U(18) \supset (U_c(3) \supset SU_T(2)) \times \\
&(U_{sd}(6) \supset U_d(5) \supset O_d(5) \supset O_d(3)), \\
&U(18) \supset (U_c(3) \supset SU_T(2)) \times \\
&(U_{sd}(6) \supset O_{sd}(6) \supset O_d(5) \supset O_d(3)), \\
&U(18) \supset (U_c(3) \supset SU_T(2)) \times \\
&(U_{sd}(6) \supset SU_{sd}(3) \supset O_d(3)). \qquad (1)
\end{aligned}$$

These group chains are called the $U(5)$, $O(6)$ and $SU(3)$ limits, and they describe the vibrational, γ-unstable and rotational motion, respectively. These limits have been used in the microscopic study of the IBM-3[19,23].

The IBM-3 Hamiltonian can be written as

$$H = \epsilon_s \hat{n}_s + \epsilon_d \hat{n}_d + H_2, \qquad (2)$$

where

$$\begin{aligned}
H_2 = &\frac{1}{2}\sum_{L_2T_2} C_{L_2T_2}((d^\dagger d^\dagger)^{L_2T_2} \cdot (\tilde{d}\tilde{d})^{L_2T_2}) + \\
&\frac{1}{2}\sum_{T_2} B_{0T_2}((s^\dagger s^\dagger)^{0T_2} \cdot (\tilde{s}\tilde{s})^{0T_2}) + \\
&\sum_{T_2} A_{2T_2}((s^\dagger d^\dagger)^{2T_2} \cdot (\tilde{d}\tilde{s})^{2T_2}) + \\
&\frac{1}{\sqrt{2}}\sum_{T_2} D_{2T_2}((s^\dagger d^\dagger)^{2T_2} \cdot (\tilde{d}\tilde{d})^{2T_2}) + \\
&\frac{1}{2}\sum_{T_2} G_{0T_2}((s^\dagger s^\dagger)^{0T_2} \cdot (\tilde{d}\tilde{d})^{0T_2}). \qquad (3)
\end{aligned}$$

The symbols T_2 and L_2 represent the two-boson isospin and angular momentum. The parameters A, B, C, D and G are the two-body matrix elements. There has been microscopic study of these parameters[24]. The Hamiltonian can also be expressed in terms of the Casimir operators which is convenient to analyze the dynamical symmetry nature. In Casimir operator form, the Hamiltonians is

$$H = \lambda C_{2U_{sd}(6)} + a_T T(T+1) + \varepsilon C_{1U_d(5)} + \gamma C_{2O_{sd}(6)} + \eta C_{2SU_{sd}(3)} + \beta C_{2U_d(5)} + \delta C_{2O_d(5)} + a_L C_{O_d(3)}. \quad (4)$$

The λ parameter determines the position of the mixed symmetry states. They occur when the motions of the protons and neutrons are not in phase. These states are characterized by strong $M1$ transitions to the full symmetry low lying states, and they have been observed in various nuclei. Typically, the representative states are, in the rotational nuclei, a 1^+ scissor mode at ~ 3MeV[25], while in the vibrational and γ-soft nuclei, a state with $J = 2^+$ at ~ 2MeV[26—28]. Mixed symmetry states in ^{66}Zn isotope is especially interesting. Recent experimental and theoretical study by Gade et al.[29] suggests that this nucleus is better described by a symmetry close to $O(6)$. Elliott et al.[30] performed a systematic study for pf-shell nuclei by mapping boson's Hamiltonian into shell model, and showed that, at low energy, states can be approximately classified by $U(6)$ representation $[N]$ for the full symmetry state and $[N-1,1]$ or $[N-2,2]$ for the mixed symmetry state. It will be interesting to see if this is born out in this calculation. The parameters of the Hamiltonian Eq. (3) used to describe the Zn-isotopes in this work are given in Table 1. The values have been chosen so as to obtain an optimum description of the low energy spectra.

The $E2$ transition can be calculated by the following isoscalar and isovector transition operators $Q = Q^0 + Q^1$ Ref. [31], where

$$Q^0 = \alpha_0\sqrt{3}[(s^+\hat{d})^{20} + (d^+\hat{s})^{20}] + \beta_0\sqrt{3}[(d^+\hat{d})]^{20}, \qquad (5)$$

$$Q^1 = \alpha_1\sqrt{2}[(s^+\hat{d})^{21} + (d^+\hat{s})^{21}] + \beta_1\sqrt{2}[(d^+\hat{d})]^{21}. \qquad (6)$$

The $M1$ transition is also a one boson operator with an isoscalar part and an isovector part $M = M^0 + M^1$, where

$$M^0 = g_0\sqrt{3}(d^+\hat{d})^{10} = g_0 L/\sqrt{10}, \qquad (7)$$

$$M^1 = g_1\sqrt{2}(d^+\hat{d})^{11}, \qquad (8)$$

where g_1 and g_0 are the isovector and isoscalar g-factor respectively and L is the angular momentum operator.

Table 1. The parameters of the IBM-3 Hamiltonian used for the description of the Zn-isotopes.

Nucleus	^{60}Zn	^{62}Zn	^{64}Zn	^{66}Zn
$\epsilon_{s_\nu}=\epsilon_{s_\pi}$	0.505	0.708	1.223	1.380
$\epsilon_{d_\nu}=\epsilon_{d_\pi}$	1.656	1.914	2.526	2.737
$A_i(i=0,1,2)$	−5.600, −1.780, 1.780	−5.534, −1.846, 1.846	−5.350, −2.026, 2.026	−5.296, −2.084, 2.084
$C_{i0}(i=0,2,4)$	−4.777, −5.406, −5.602	−4.706, −5.790, −5.286	−4.936, −5808, −4.926	−4.666, −5.772, −4.946
$C_{i2}(i=0,2,4)$	2.608, 1.978, 1.778	2.674, 1.590, 2.094	2.444, 1.572, 2.452	2.714, 1.608, 2.434
$C_{i1}(i=1,3)$	−1.750, −1.890	−2.166, −1.806	−2.580, −1.950	−2.552, −1.962
$B_i(i=0,2)$	−5.430, 1.950	−5.354, 2.026	−5.224, 2.150	−5.200, 2.180
$D_i(i=0,2)$	0.000, −0.380	0.000, −0.402	0.000, −0.290	0.000, −0.214
$G_i(i=0,2)$	−0.380, 0.000	−0.402, 0.000	−0.290, 0.000	−0.214, 0000
$\alpha_0=\beta_0$	0.050	0.050	0.053	0.035
$\alpha_1=\beta_1$	0.055	0.055	0.055	0.055
g_0	0.000	0.000	0.000	0.000
g_1	1.000	1.000	1.100	1.600

3 Excitation energy

The Zn isotopes ($Z=30$) have $N_\pi=1$ proton boson, relative to the ($Z=28$) shell. The neutron boson number, also relative to the 28 shell, goes from 2 to 5 ($A=60$—66). According to this, both proton and neutron boson are of particle-type.

^{60}Zn This nucleus is one with $Z=N$, in the *pf*-shell. Studies of the existence of isospin excitations have received wide interest in the last few years[32—36]. The more recent study is performed using the decay properties of ^{60}Ga[37]. According to this study, the level 2.558 MeV has been assigned to the 2_2^+ state. It has also observed an isospin excited state of 2^+ ($T=1$) at 4.851 MeV. Svensson et al.[38] have observed a superdeformed band in this nucleus. Langanke et al.[32] performed a shell model Monte Carlo calculation in the *pf*-shell with pairing-plus-quadrupole Hamiltonian. Our calculated levels are shown in Fig. 1. Clear reproduction of the low-lying structural features observed in the experimental data can be seen, especially those of the isospin excitation states. In this figure the energy levels have been arranged into groups according to the isospin and the dynamical symmetry structure. As it can be seen, our results agree very well with the experiment. In particular, all low-lying 2^+ states with different isospin values are reproduced correctly. The level at 5.337 MeV, with possible angular momentum $J=$

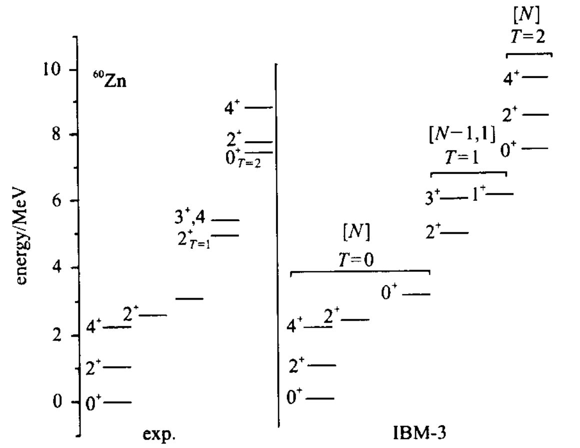

Fig. 1. Comparison between lowest excitation energy bands ($T=T_z$, T_z+1 and T_z+2) of the IBM-3 calculation and experimental excitation energies of ^{60}Zn. The experimental data are taken from Refs. [37, 39].

3^+, 4^+ is assigned to the 3_1^+ state in our calculation and its wave function has a large predominant $[N-1,1]$ partition. Our calculated second 0^+ state at 3.058 MeV is closed to the observed state at 3.035 MeV. The comparison of experimental and theoretical excitation energies shows it is most probable that the 2_3^+ state is the lowest mixed symmetry state. This state comes from $[N-1,1]$ with $T=1$. A similar result is expected for 3_1^+. The 0_3^+ ($T=2$) state is the band head of an isospin excitation with $T=T_z+2$, and it is quite closed to the experimental level at 7.380 MeV. The 2_4^+ and 4_2^+ states are also members of this band. More detailed informations on these states can be derived from electromagnetic transitions de-exciting from these states. Since no absolute values for $E2$ and $M1$ transition probabilities are known, the IBM-3 results are the relative values, and are illustrated in Fig.5. The agreement is good.

$^{62-66}$Zn nuclei In Figs.2—4 we show the results of our calculation for ground state band and the gamma band in the $^{62-66}$Zn isotopes. They are well reproduced. We include the known 0_2^+ states in the Zn isotopes and their positions are reproduced reasonably well. Meanwhile, the 0_3^+ states in the IBM-3 results are in good agreement with the observed ones in ^{64,66}Zn isotopes. The deviations between calculation and experiment may be attributed to the mixing of the collective excitation with quasi-particle excitations.

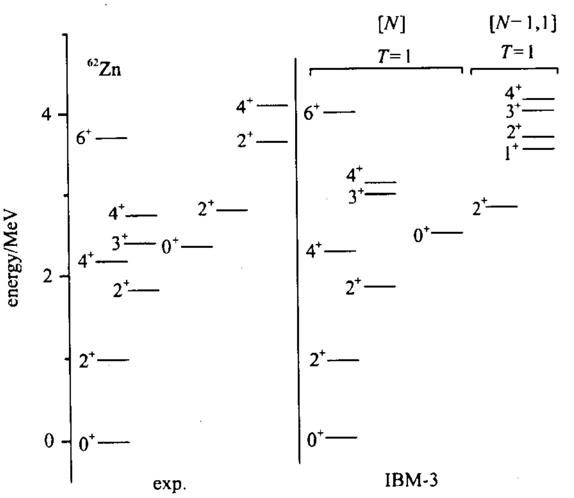

Fig.2. Comparison between lowest excitation energy bands of the IBM-3 calculation and experimental excitation energies of ^{62}Zn. The experimental data are taken from Ref.[39].

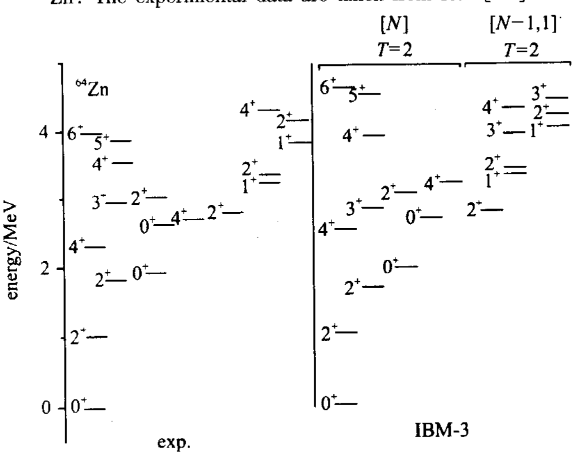

Fig.3. Comparison between lowest excitation energy bands of the IBM-3 calculation and experimental excitation energies of ^{64}Zn. The experimental data are taken from Ref.[39].

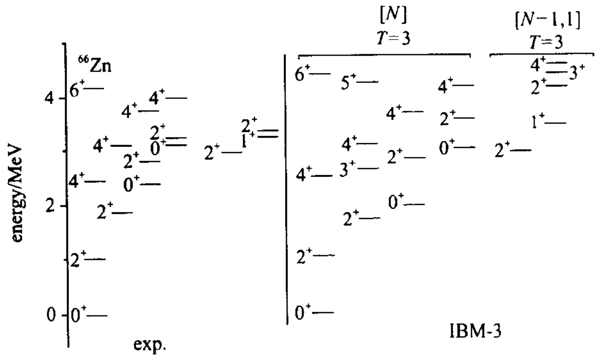

Fig.4. Comparison between lowest excitation energy bands of the IBM-3 calculation and experimental excitation energies of ^{66}Zn. The experimental data are taken from Ref.[39].

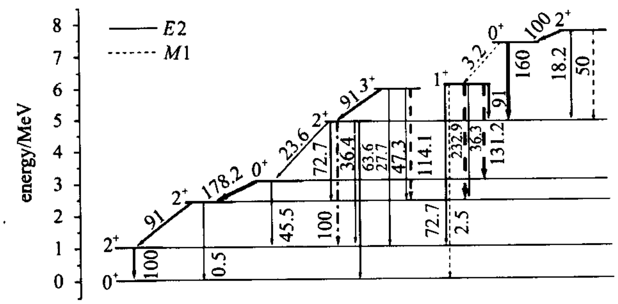

Fig.5. Energy levels ($T = T_z, T_z + 1, T_z + 2$) and relative electromagnetic transition probabilities for ^{60}Zn.

4 Mixed symmetry state

In order to identify the lowest mixed symmetry state we analyze the wave function of low lying 2^+ states in these nuclei. The main components of the wave function for 2_3^+ and 2_4^+ are given as follows, respectively,

$$|2_3^+\rangle = -0.573|s_\nu^2 d_\pi\rangle + 0.405|s_\nu s_\pi d_\nu\rangle - 0.527|s_\delta^2 d_\nu\rangle + 0.405|s_\nu s_\delta d_\nu\rangle + \cdots,$$

$$|2_4^+\rangle = 0.577|s_\pi(d_\nu^2)_2\rangle - 0.408|s_\nu d_\nu d_\pi\rangle + 0.577|s_\nu(d_\delta^2)_2\rangle - 0.408|s_\delta d_\nu d_\pi\rangle + \cdots$$

for ^{62}Zn isotope,

$$|2_3^+\rangle = -0.696|s_\nu^3 d_\pi\rangle + 0.401|s_\nu^2 s_\pi d_\nu\rangle + 0.401|s_\nu^2 s_\delta d_\delta\rangle - 0.401|s_\nu s_\delta^2 d_\nu\rangle + \cdots,$$

$$|2_4^+\rangle = 0.560|(d_\nu^3)_0 d_\pi\rangle + 0.625|(d_\nu^3)_3 d_\pi\rangle - 0.292|(d_\nu^2)_2(d_\delta^2)_2\rangle - 0.163|(d_\nu^2)_2(d_\delta^2)_4\rangle + \cdots$$

for ^{64}Zn isotope, and

$$|2_3^+\rangle = 0.516|s_\nu(d_\nu^3)_0 d_\pi\rangle + 0.571|s_\nu(d_\nu^3)_3 d_\pi\rangle + 0.421|s_\pi(d_\nu^4)_2\rangle - 0.199|s_\nu(d_\nu^2)_4(d_\delta^2)_2\rangle + \cdots,$$

$$|2_4^+\rangle = -0.761|s_\nu^4 d_\pi\rangle + 0.381|s_\nu^3 s_\pi d_\nu\rangle +$$

$0.381|s_\nu^3 s_\delta d_\delta\rangle - 0.125|s_\nu^2(d_\nu^2)_0 d_\pi\rangle + \cdots$

for ^{66}Zn isotope.

In these expressions, we have labeled the angular momentum sub-total for the d-boson configurations. For instance, $|(d_\nu^3)_3 d_\pi\rangle$ means that the 3 d_ν bosons couple to $L_{d_\nu} = 3$ and then they couple with a d_π boson to form an $L = 2$ basis state. The wave functions show that the 2_3^+ state is the mixed symmetry in the ^{62,64}Zn isotopes, while the 2_4^+ is the mixed symmetry state in the ^{66}Zn, and all these states are from the $s^{N-1}d$ configuration. We found that the 2_2^+ state is a totally symmetric state, it is almost a pure $s^{N-2}d^2$ configuration, and has almost equal amplitudes in the $|s_\nu^{N_\nu-1}d_\nu d_\pi\rangle$ and $|s_\nu^{N_\nu-2}s_\pi d_\nu^2\rangle$ components. For the other 2^+ states, large mixed symmetry components are included in 2_5^+ state in the ^{62,64}Zn and 2_6^+ state in the ^{66}Zn (i.e. 2_{2ms} state with $[N-1,1]$ partition). From Fig.2—4 one can see that the energies of 1^+ states are in good agreement with the available data, and they belong to partition $[N-1,1]$. The next higher mixed symmetry states come from the partition $[N-2,2]$, we find that such states are about 5 MeV or higher and the lowest example is a 1^+ states in ^{64,66}Zn at 4.92 MeV and 5.42 MeV, respectively.

5 Electromagnetic transitions

Our results for electromagnetic transition probabilities are summarized in Tables 2—4. The parameters of the $E2$ and $M1$ operators were fitted to experimental $B(E2;\ 2_1^+\to 0_1^+)$ and $B(M1;\ 2_{ms}^+\to 2_1^+)$. The $B(E2)$ values in the g.s.b. are calculated up to the 6^+ states, and are well reproduced within the experimental errors. From these tables we see that the 2_1^+, 2_2^+ and 3_1^+ states are connected by very strong $E2$ transitions, indicating they are of full symmetry. In contrast, we see in these tables that the 2_3^+ and 3_2^+ states decay to 2_1^+ and 2_2^+ states by strong $M1$ transitions and weak $E2$ transitions in both ^{62,64}Zn isotopes. It is also true for 2_4^+ and 3_2^+ states in the ^{66}Zn isotope. We find that the mixed symmetry state transition $2_m^+\to 2_1^+$ has an $E2/M1$ mixing ratio 0.099, 0.095 and 0.071 for $^{62-66}$Zn, respectively. They are nearly pure $M1$ transitions.

Table 2. Experimental[39] and calculated $B(E2)(e^2b^2)$ and calculated $B(M1)(\mu_N^2)$ for ^{62}Zn isotope.

$J_i^+\to J_f^+$	$B(E2)$		$B(M1)$	
	Exp.	Cal.	Exp.	Cal.
$2_1^+\to 0_1^+$	0.0170(1)	0.0171		
$2_2^+\to 0_1^+$	0.0004(1)	0.0002		
$2_2^+\to 2_1^+$	0.0175(6)	0.0202	0.0537	0.0000
$2_3^+\to 2_1^+$		0.0016		0.0804
$2_3^+\to 2_2^+$		0.0018		0.0000
$2_3^+\to 0_1^+$		0.0042		
$0_2^+\to 2_1^+$		0.0001		
$0_2^+\to 2_2^+$		0.0140		
$0_3^+\to 2_1^+$		0.0086		
$0_3^+\to 2_2^+$		0.0176		
$0_3^+\to 2_3^+$		0.0044		
$1_1^+\to 0_1^+$				0.0044
$1_1^+\to 2_1^+$		0.0049		0.0000
$1_1^+\to 2_2^+$		0.0012		0.1392
$1_1^+\to 2_3^+$		0.0453		0.0000
$3_2^+\to 2_2^+$		0.0016		0.0682
$4_1^+\to 2_1^+$	0.0378(17)	0.0202		
$4_2^+\to 2_1^+$		0.0015		
$4_2^+\to 2_2^+$		0.0001		
$4_2^+\to 4_1^+$	0.0262(87)	0.0066		0.0000
$6_1^+\to 4_1^+$	0.0276(48)	0.0141		

Table 3. Experimental[39] and calculated $B(E2)(e^2b^2)$ and calculated $B(M1)(\mu_N^2)$ for ^{64}Zn isotope.

$J_i^+\to J_f^+$	$B(E2)$		$B(M1)$	
	Exp.	Cal.	Exp.	Cal.
$2_1^+\to 0_1^+$	0.0328(1)	0.0334		
$2_2^+\to 0_1^+$	0.0004(1)	0.0004		
$2_2^+\to 2_1^+$	0.0608(76)	0.0446	0.0013(7)	0.0000
$2_3^+\to 2_1^+$	0.0198(182)	0.0018	0.0895(537)	0.1030
$2_3^+\to 2_2^+$		0.0014		0.0000
$2_3^+\to 0_1^+$		0.0061		
$0_2^+\to 2_1^+$	0.0001(1)	0.0001		
$0_2^+\to 2_2^+$	0.0912(121)	0.0212		
$0_3^+\to 2_1^+$	0.0258(106)	0.0218		
$1_1^+\to 0_1^+$			0.002(1)	0.0066
$1_1^+\to 2_2^+$		0.0011		0.1577
$3_1^+\to 2_1^+$	0.0002(1)	0.0002	0.0057	0.0000
$3_1^+\to 2_2^+$	0.0002(1)	0.0298	0.0501	0.0000
$3_2^+\to 2_2^+$	0.0027	0.0016	0.0591(179)	0.0772
$4_1^+\to 2_1^+$	0.0441(91)	0.0446		
$4_2^+\to 2_1^+$	0.0011(3)	0.0002		
$4_2^+\to 2_2^+$	0.0456(91)	0.02134		
$4_2^+\to 4_1^+$	0.0136(106)	0.0196	0.0268(71).	0.0000
$6_1^+\to 4_1^+$	0.0349(91)	0.0412		

Table 4. Experimental[29,39] and calculated $B(E2)(e^2b^2)$ and calculated $B(M1)(\mu_N^2)$ for ^{66}Zn isotope.

$J_i^+ \to J_f^+$	$B(E2)$ Exp.	$B(E2)$ Cal.	$B(M1)$ Exp.	$B(M1)$ Cal.
$2_1^+ \to 0_1^+$	0.0283(11)	0.0294		
$2_2^+ \to 0_1^+$	$0.53(20)\times10^{-4}$	0.0002		
$2_2^+ \to 2_1^+$	≥0.0750	0.0430		0.0000
$2_3^+ \to 0_1^+$		0.0054		
$2_4^+ \to 2_1^+$	0.0158(628)	0.0016	0.21(3)	0.2010
$0_2^+ \to 2_2^+$		0.0123		
$0_3^+ \to 2_1^+$		0.0265		
$1_1^+ \to 0_1^+$			0.07(2)	0.0100
$1_1^+ \to 2_1^+$	0.0004^{+1}_{-2}	0.0080	0.0014(5)	0.0000
$1_1^+ \to 2_2^+$		0.0010	0.19(6)	0.2900
$1_1^+ \to 2_4^+$	0.0750(270)	0.0292	·	0.0000
$3_1^+ \to 2_1^+$		0.0002		0.0000
$3_1^+ \to 2_2^+$		0.0329		0.0000
$3_2^+ \to 2_2^+$		0.0013		0.1420
$4_1^+ \to 2_1^+$	0.0559^{+168}_{-105}	0.0430		
$4_2^+ \to 2_1^+$		0.0001		
$4_2^+ \to 2_2^+$		0.0234		
$4_2^+ \to 4_1^+$		0.0216		0.0000
$6_1^+ \to 4_1^+$	0.0200^{+200}_{-80}	0.0454		

6 Conclusions

We have investigated the $^{60-66}$Zn isotopes using IBM-3. The main focus of this investigation has been the isospin and symmetry structure in these nuclei. A number of isospin excitation states have been found up to 4 MeV in the ^{60}Zn ($N=Z$) nucleus, where the 2_3^+ level at 4.85 MeV is the $T=1$ band head, and the 0_3^+ state at 7.38 MeV is the head of $T=2$ band. When we did the calculation for this nucleus, we did not take into account of the experimental 2_2^+ states in the fitting. However, after the calculation, the calculated 2_2^+ state result agrees very well with the recent experimental data[37]. The present IBM-3 wave functions have been stringently tested in the energy level and electromagnetic transition comparisons with experiments. By inspecting the wave function, the (2_3^+, 2_5^+) and (2_4^+, 2_6^+) are the first and second mixed symmetry 2^+ states in the ^{62,64}Zn and ^{66}Zn respectively. From the Casimir form of the Hamiltonian, we found that these even-even Zn isotopes are in the transition from $U(5)$ to $O(6)$ dynamical symmetry. The $U(6)$ label is also an approximately good quantum number.

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$^{60-66}$Zn 同位素核的同位旋与混合对称激发*

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摘要 利用相互作用玻色子模型3研究了$^{60-66}$Zn同位素的能级结构.通过对波函数的分析,研究了这些核中的混合对称态.确认了^{60}Zn核中的同位旋激发态.对计算的能级和跃迁几率同实验数据进行了比较.得到的这些结果以及计算中确定的参数值表明Zn同位素是从振动到gamma不稳定的转动的过渡核.

关键词 相互作用玻色子模型 同位旋激发态 混合对称态

2003－08－04收稿

*国家自然科学基金(10047001),国家重点基础研究发展规划项目(G200077400)资助

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