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An IBM2 Description on the Staggering Phenomenon in the Barium Isotopes

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Abstract

A description on the even-even Barium isotopes for A=128 to 136 and 140 in the framework of neutron-proton Interacting Boson Model is carried out. By introducing the quadrupole interactions among like bosons into the Hamiltonian, the staggering phenomenon in the quasi-γ bands are reproduced pretty well. The physical mechanism behind the improvement are discussed.

I. Introduction

Since the Interacting Boson Model(IBM) of nuclear structure was put forward by Arima and Iachello[1], there have been many discussions on the IBM description of even-even Ba isotopes. In the original version of the Interacting Boson Model(IBM1), in which the neutron-, proton-boson degrees of freedom are not distinguished, the nuclei in the Ba region are regarded to belong to the $O(6)$ limit region[2], and ^{132}Ba has been taken to be an example of the one with $O(6)$ symmetry[3]. In the neutron-proton Interacting Boson Model(IBM2)[4] which is obtained by mapping the coherent pairs of identical nucleons with $J = 0$ and $J = 2$ on the states of neutron and proton bosons s_ν, d_ν and s_π, d_π, there are also lots of works to describe the properties of Ba isotopes[5–8], by which one know that the Ba isotopes are the example in the transition range with change from $O(6)$ (around neutron number 78) toward $SU(3)$ (around neutron number 66), and to $U(5)$ (around neutron number 54)[6].

Although most properties of the Ba isotopes have been described, the quasi-γ bands of the energy spectra have not been reproduced with satisfactory precision. In the $O(6)$ limit of IBM, the energy levels in quasi-γ band exhibits much more obvious sequential doublets $(3^+_\gamma, 4^+_\gamma)$, $(5^+_\gamma, 6^+_\gamma)$, $\cdots\cdots$, than the

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ones observed in experiments. This is the so called staggering phenomenon in IBM and it was regarded as the difficulty of the $O(6)$ limit. In IBM1, It can be eliminated by considering the three-body interactions among d-bosons[9–12]. However there was not much work to discuss this problem in IBM2. Recently, as the quadrupole interactions among like bosons were taken into account, it shone a light on solving the problem in IBM2[8,13–15]. In Ref. [13-15], it was shown that the staggering of nuclear energy levels in the quasi-γ band is determined by the competition between the quadrupole interactions among like bosons and those among unlike bosons. By means of adjusting the interaction strength among like bosons with respect to that among unlike bosons, the staggering phenomenon can be reproduced quite well.

In this paper, the mechanism of the improvement in the approach will be discussed, meanwhile it will be applied to the Ba isotopes to describe the quasi-γ bands precisely. In section 2, the approach will be reviewed briefly, and the physical mechanism of the improving will be discussed. In section 3, we apply the approach to even-even Ba isotopes $^{128-136}$Ba and ^{140}Ba. The calculated energy spectra are given. And a brief discussion follows in section 4.

II. The Approach and its Mechanism

In general, the Hamiltonian in IBM2 is taken as

$$H = \varepsilon \hat{n}_d + \kappa \hat{Q}^{(2)}_\pi \cdot \hat{Q}^{(2)}_\nu + V_{\pi\pi} + V_{\nu\nu} + M_{\pi\nu}, \quad (1)$$

where ε is the d-boson energy, κ is the strength of the quadrupole interaction between neutron- and proton-bosons. The quadrupole operator is given as

$$\hat{Q}^{(2)}_\rho = (s^\dagger_\rho \tilde{d}_\rho + d^\dagger_\rho s_\rho)^{(2)} + \chi_\rho (d^\dagger_\rho \tilde{d}_\rho)^{(2)}, \qquad (\rho = \pi, \nu). \quad (2)$$

$V_{\pi\pi}$ and $V_{\nu\nu}$ are the neutron-neutron and proton-proton d-boson interactions, which can be written as

$$V_{\rho\rho} = \frac{1}{2} \sum_{K=0,2,4} \sqrt{2L+1}\, C^{(K)}_\rho \left[(d^\dagger_\rho d^\dagger_\rho)^{(K)} (\tilde{d}_\rho \tilde{d}_\rho)^{(K)} \right]^{(0)}, \qquad (\rho = \pi, \nu). \quad (3)$$

The last term $M_{\pi\nu}$ is the Majorana interaction, which has the form

$$M_{\pi\nu} = \frac{1}{2}\xi_2 (s^\dagger_\nu d^\dagger_\pi - s^\dagger_\pi d^\dagger_\nu)^{(2)} \cdot (s_\nu \tilde{d}_\pi - s_\pi \tilde{d}_\nu)^{(2)} + \sum_{\lambda=1,3} \xi_\lambda (d^\dagger_\nu d^\dagger_\pi)^{(\lambda)} \cdot (\tilde{d}_\pi \tilde{d}_\nu)^{(\lambda)}. \quad (4)$$

The Hamiltonian (1) has been used to calculate many of the even-even heavy and medium heavy nuclei. Generally, the calculated results agree with experiments well. However, there are still obvious staggering phenomena in the quasi-γ bands of the calculated spectra.

Nevertheless, it has been shown[13–15] that if the Hamiltonian is taken as

$$H = \varepsilon \hat{n}_d + \kappa \hat{Q}_\pi^{(2)} \cdot \hat{Q}_\nu^{(2)} + \kappa'(\hat{Q}_\pi \cdot \hat{Q}_\pi + \hat{Q}_\nu \cdot \hat{Q}_\nu) + M_{\pi\nu}, \tag{5}$$

the calculated staggering phenomenon can be reduced efficiently. Moreover, as the ratio κ'/κ changes from 0 to 1/2, the staggering in the quasi-γ band disappears gradually. It means that the aspect of the quasi-γ band is determined by the competition between the quadrupole interactions among like bosons and those among unlike bosons. What is the physical mechanism behind this improvement?

A thorough investigation on the dynamical limits of IBM shows that the staggering phenomenon in the quasi-γ band of $O(6)$ limit is resulted from the breaking of dynamical symmetry. The Hamiltonian of the system with $O(6)$ symmetry is

$$H = A_4\, C_{2O(6)} + B\, C_{2O(5)} + C\, C_{2O(3)}, \tag{6}$$

where C_{2G} is the Casimir operator of the group G. The energy of the state with $O(6)$ symmetry can then be expressed as

$$E_{O(6)}(L) = A_4\sigma(\sigma+4) + B\tau(\tau+3) + CL(L+1), \tag{7}$$

where $\langle\sigma\rangle$, (τ) are the irreducible representations (IRRPs) of the groups $O(6)$, $O(5)$ respectively, L is the angular momentum of the state. In the quasi-γ band, the angular momenta of the doublets $(3^+,4^+)$, $(5^+,6^+)$, $\cdots\cdots$, are the different IRRPs of $O(3)$ belonging to the same IRRPs $\langle\sigma\rangle$, (τ) of $O(6)$, $O(5)$. Then the quantum number σ, τ in the expression (7) for the states in a doublet are the same, but they are different for the others. For instance, 3^+_γ, 4^+_γ correspond to $\sigma = n$ (n is the total number of bosons), $\tau = 3$, but 5^+_γ, 6^+_γ to $\sigma = n$, $\tau = 4$. Because of the symmetry breaking, the relation $C \ll B \ll A_4$ is hold, then the energy difference between the two states in a doublets is much smaller than that between the neighboring doublets. The distribution of the levels in the quasi-γ band is thus rather nonuniform with compared to that in the ground state band, and much more obvious than the observed in experiments. In the other case, the energy spectrum of triaxial rotor displays doublets $(2^+,3^+)$, $(4^+,5^+)$, $\cdots\cdots$[16]. It has been shown that the triaxial rotor potential has close relation with $SU^*(3)$ symmetry[17,18]. It is quite evident that, with a interaction possessing proper $SU^*(3)$ symmetry being introduced into the Hamiltonian of $O(6)$ limit, the staggering can be reduced.

Looking over eqs.(1) and (5), one know that the difference between them is the interactions among like bosons. Eq.(1) considers the interactions among like d-bosons, however eq.(5) takes the quadrupole interaction among like s- and d-bosons into account. Dynamical symmetry analysis shows that the

Hamiltonian (5) holds $O(6)$, $U(5)$, $SU(3)$, $SU^*(3)$ and other symmetries, and the $SU^*(3)$ component can be strengthened by taking appropriate strength κ' and oppositely signed χ_π, χ_ν. As mentioned above, in the approach, the energy spectrum is determined just in the way of regulating the interaction strength κ' with respect to a well situated κ, and keeping χ_π and χ_ν with opposite sign. This procedure reinforce the $SU^*(3)$ symmetry of the Hamiltonian, a suitable triaxial rotor potential is thus added to the Hamiltonian, so that the characteristic of the quasi-γ band can be reproduced pretty well with the approach.

III. Applications to Ba Isotopes

The discussion in last section shows that eq.(5) is an appropriate Hamiltonian with which the low-lying excited states of even-even nuclei can be described well. In this section we calculate the energies of the low-lying excited state of even-even Ba isoropes by employing the Hamiltonian (5).

For the even-even Ba isotopes with A=128 to 136, there are three hole-like proton bosons and five to one hole-like neutron bosons. There are three hole-like proton bosons and one particle-like neutron bosons in ^{140}Ba. The quantities ε, κ, κ', χ_π and χ_ν, which determine the structure of the energy spectrum, may depend, in principle, on both proton and neutron boson numbers n_π, n_ν. However, in order to reduce the number of free parameters and in agreement with microscopic calculations, we take the χ_ρ parameters in the usual way that $\chi_\pi = -0.600$ keeps constant, χ_ν changes smoothly with neutron-boson number (i.e. χ_π depends only on n_π and χ_ν on n_ν). Meanwhile, we maintain $\xi_1 = \xi_2 = 0.100$MeV as constants for the whole isotope chain to give a overall improvement on the spectra. The spectra are not sensitive to the parameter ξ_3 except for the position of 1^+_1 state. Since there is no experimental evidence for the 1^+_1 states of Ba isotopes, ξ_3 and other parameters such as ε, κ, κ' are chosen separately for each nucleus. The parameters we used in the calculation are shown in Table 1.

Table 1. Parameters used to calculate energy spectra of Ba isotopes ($\chi_\pi = -0.600$, $\xi_1 = \xi_2 = 0.100$MeV)

	^{128}Ba	^{130}Ba	^{132}Ba	^{134}Ba	^{136}Ba	^{140}Ba
ε(MeV)	0.600	0.620	0.700	0.780	1.000	0.770
κ(MeV)	−0.175	−0.185	−0.190	−0.200	−0.180	−0.210
κ'(MeV)	−0.001	−0.0005	−0.003	−0.010	−0.005	−0.001
ξ_3(MeV)	−0.200	−0.170	−0.300	−0.350	−0.500	−0.200
χ_ν	0.600	0.550	0.370	0.330	0.500	0.600

One may notice that ε is increased smoothly from ^{128}Ba to ^{136}Ba. The absolute value of parameter κ increases with the valence nucleon (hole-like) decreasing except for ^{136}Ba. The parameter κ' for all the nuclei are quite small, and the χ_ν changes slickly.

With the Hamiltonian (5) and the parameters listed in table 1, the energy spectra of even-even nuclei $^{128-136}$Ba and ^{140}Ba are calculated. The calculated results are plotted against their experimental counterparts in figure 1. For comparison, the IBM2 calculated results of Puddu *et al.*[6] and Sevrin *et al.*[8] are also drawn. In order to make comparison more clearly, the states have been separated into three different sets of ground state band, quasi-γ band and side band. In general, the ground state band fits well with the experimental data, especially, present calculation gives more rotational spectrum at higher spins except ^{134}Ba and ^{136}Ba. In ^{134}Ba (^{136}Ba) the 10_1^+ (6_1^+) state is so low that the doublets (8_1^+, 10_1^+) ((4_1^+, 6_1^+)) are formed. If the 10_1^+ and 6_1^+ states are confirmed in experiments, an additional effort has to be made to understand them. The figure show also that there are obvious improvements on the fitting of the quasi-γ bands. Globally, the theoretical calculations agree with experimental data very well. As in ^{128,130}Ba and ^{140}Ba, the experimental spectra do show some degrees of staggering, in the calculation a very small κ' has to be used. In ^{132}Ba and ^{134}Ba, the staggering is almost completely removed. As for the side bands, the agreement between the present calculation and the experiments is also satisfactory with the exception of the 2_3^+ state of ^{132}Ba and the 0_2^+ state of ^{136}Ba. In ^{136}Ba the 0_2^+ and 0_3^+ states are too high compared with experiment. These higher levels in side bands, most of them with spin 0, may be the mixing states of boson configuration and intruder configurations.

The scissor state 1_1^+, which is the state with mixed symmetry, depends on the Majorana interaction, so that the levels of the 1_1^+ states of the Ba isotopes are determined by the parameter ξ_3. The calculated energies of all the 1_1^+ states of these nuclei are displyed in table 2. They are all larger than 2.00 MeV, which are close to the observed energy of 1_1^+ state of other nucleus.

Table 2. The calculated energies of the 1^+ state of Ba isotopes

	^{128}Ba	^{130}Ba	^{132}Ba	^{134}Ba	^{136}Ba	^{140}Ba
E(1^+)(MeV)	2.142	2.094	2.121	2.222	2.449	2.110

IV. Discussions

In this paper,the energy spectra of even-even Ba isotopes $^{128-136}$Ba and ^{140}Ba are described in the framework of neutron-proton Interacting Boson Model. The theoretical predictions agree with experimental data quite well. An improvement is made in the quasi-γ band and the staggering phenomenon is reproduced successfully by introducing the quadrupole interactions among like bosons. Meanwhile the physical mechanism behind the improvement on the

fitting of the staggering phenomenon in the approach is discussed. It manifests that the grounds for reducing the staggering is that the consideration on the $\hat{Q}_p^{(2)} \cdot \hat{Q}_p^{(2)}$ interactions adds a rational triaxial rotor potential to the Hamiltonian with rather strong $O(6)$ symmetry. However, the microscopic implication of such interactions remains an interasting question. This may be the residual interactions among like nucleons, because some evidences show that, although the dominant forces among like nucleons are of the pairing type, it is still necessary to consider some quadrupole forces among them in the BCS treatment on the system with all neutrons or all protons[20]. On the other hand, we found that, in ^{132}Ba and ^{136}Ba, the levels of 2_3^+ and 0_2^+ states cannot be reproduced in the approach. Since there are few experimental evidences of E2 and M1 transitions for Ba isotopes, we have not discussed the electromagnetic transition rates in this paper. More works need to be done in this direction to recognize the properties of Ba isotopes in details.

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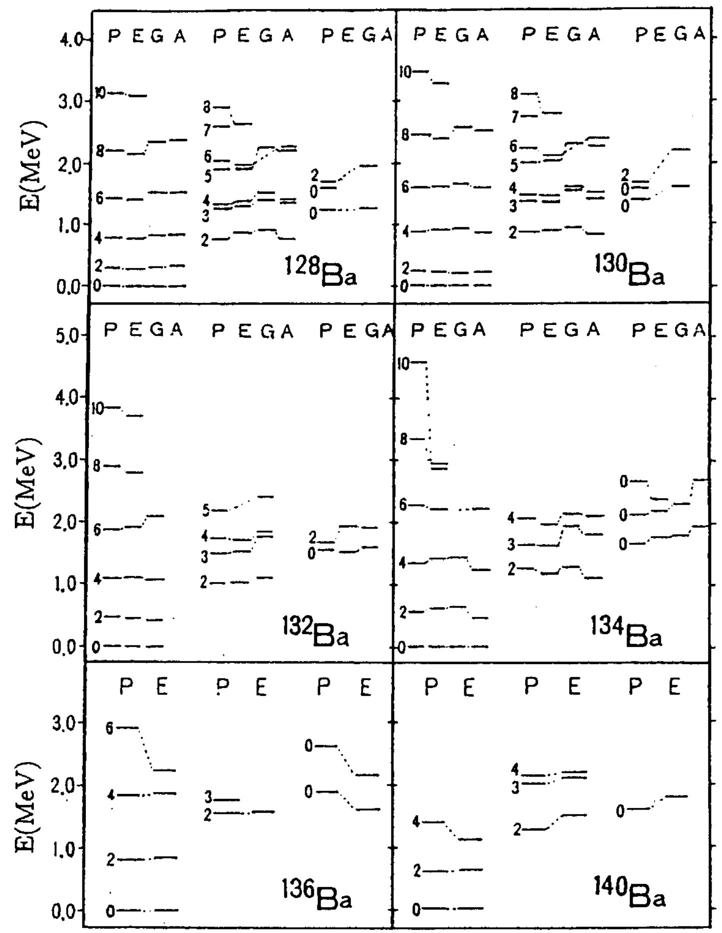

Fig. 1: Energy spectra for Ba isotopes. The column marked with P stands for the present calculation, the one with E stands for Experimental data, and the ones with G, A refer to the results of Ref.[6] and Ref.[8] respectively. The experimental data are taken from Ref.[19].