Microscopic Investigation of Magnetic Dipole Bands in ^{132}Ba

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Abstract. Nuclear structure of ^{132}Ba is investigated within a framework of the pair-truncated shell model. The model reproduces experimental energy levels of the magnetic dipole band with the $\nu(h^2_{11/2}) \otimes \pi(h_{11/2}g_{7/2})$ configuration. From analysis of its structure, it turns out that two angular momenta of valence neutrons and protons gradually close as total spin increases.

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1. Introduction

Recently, a number of $\Delta I = 1$ bands, namely magnetic dipole bands, have been experimentally found in many $A \sim 130$ nuclei [1, 2]. One of the characteristic features of the magnetic dipole bands is their strong $M1$ transitions. These bands were extensively investigated in the framework of the tilted axis cranking model [3].

Some theoretical studies of $A \sim 130$ nuclei were carried out in terms of the pair-truncated shell model (PTSM). In this model, the shell model basis states are restricted within the subspace of collective pairs. This approach reproduced well various nuclear properties in this mass region [4, 5, 6, 7, 8]. However, this model needs to be extended for a description of the magnetic dipole bands with negative parity. In this paper, we propose a new version of the PTSM which includes negative parity pairs, and apply this model to the negative parity states in ^{132}Ba.

2. Framework of the PTSM and its application to positive parity states

In order to describe the positive parity states of even-even nuclei, we adopt the $SD{+}H$ version of the PTSM [4, 6]. The building blocks of this model are angular momenta zero (S) and two (D) collective pairs, and also non-collective H pairs, which are made by two nucleons in the $0h_{11/2}$ orbitals. The many-body wave function of the even-nucleon system is created by applying the operators $S^\dagger$, $D^\dagger$ and $H^\dagger$ (the S, D and H pair-creation operators) to the closed-shell core $|-\rangle$:

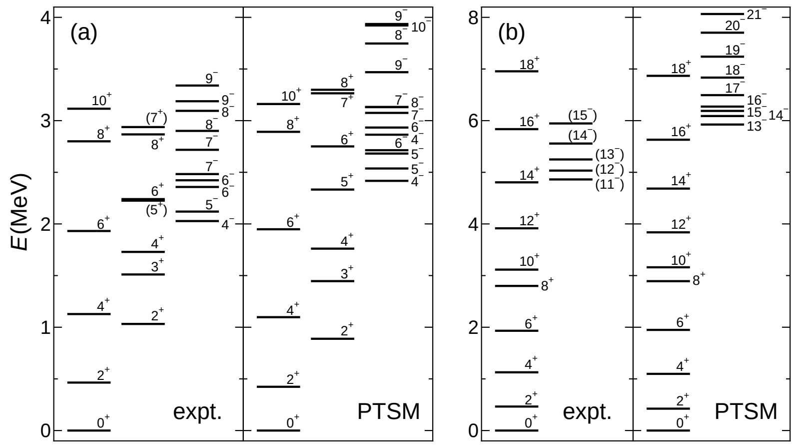

Figure 1. Comparison of energy spectrum in experiment (expt.) with that of the PTSM (PTSM). The experimental data are taken from Refs. [9, 10]. (a) Two level sequences on the left represent the yrast and yrare bands, respectively, levels on the right denote the low-lying negative parity states. (b) The level sequences on the left represent the yrast band, and the level sequences on the right, the magnetic dipole band.

$$|S^{n_s} D^{n_d} H^{n_h} I\eta\rangle = (S^\dagger)^{n_s} (D^\dagger)^{n_d} (H^\dagger)^{n_h} \left|-\right\rangle, \tag{1}$$

where I is a total angular momentum, η is an additional quantum number required to completely specify the state, and $2n_s + 2n_d + 2n_h$ gives the number of valence neutron holes or proton particles. Here we assume $n_h = 0$ or $n_h = 1$ for computational simplicity. Then a basis state of any even-even nucleus is constructed as a product of the above wave function in neutron space, $|S_\nu^{\bar{n}_s} D_\nu^{\bar{n}_d} H_\nu^{\bar{n}_h} I_\nu \eta_\nu\rangle$, and that in proton space, $|S_\pi^{n_s} D_\pi^{n_d} H_\pi^{n_h} I_\pi \eta_\pi\rangle$. In Fig. 1, the energy spectrum obtained by the PTSM is compared with experiment for ^{132}Ba, assuming the $P + QQ$ interactions with strengths given in Ref. [4]. The calculation reproduces well positive parity energy levels of the even-spin yrast band up to spin 18 [panel (b)]. For the quasi-γ band, our result gives a successful description of the energy staggering of the even-odd spin states [panel (a)]. We also calculated the $E2$ transition rates and branching ratios, and obtained a good agreement with experiment. A detailed discussion of these results is presented in Ref. [4].

3. Magnetic dipole bands

For a description of the negative parity states, we need to introduce negative parity (N_i,$i = 1, 2, 3$) pairs in addition to the S, D and H pairs.

$$N_1^{\dagger(K_1)} = \left[c_{11/2}^\dagger c_{1/2}^\dagger\right]^{(K_1)}, \tag{2}$$

$$N_2^{\dagger(K_2)} = \left[c_{11/2}^\dagger c_{3/2}^\dagger\right]^{(K_2)}, \tag{3}$$

$$N_3^{\dagger(K_3)} = \left[c_{11/2}^\dagger c_{7/2}^\dagger\right]^{(K_3)}, \tag{4}$$

where the coupled angular momenta take values of $K_1 = 5, 6$, $K_2 = 4, 5, 6, 7$, and $K_3 = 2, 3, 4, \cdots, 9$. Then the wave function of the even-nucleon system with negative

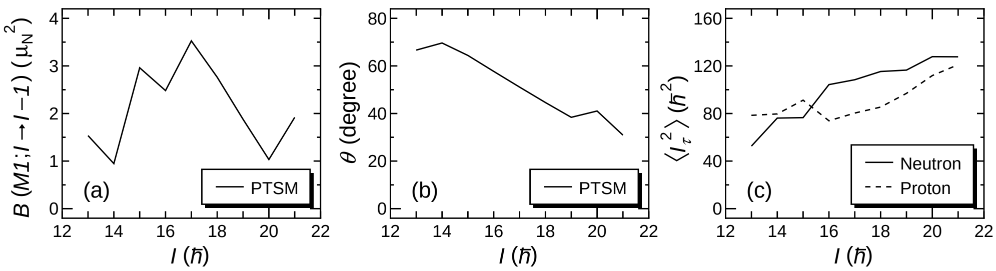

Figure 2. (a) $B(M1)$ values calculated in the PTSM. No experimental data are available for ^{132}Ba. (b) The effective angles of two angular momenta calculated in the PTSM. (c) The squares of the neutron and proton angular momenta calculated in the PTSM. Solid line indicates the squares for neutrons, and dotted line, for protons.

parity is constructed as

$$|S^{n_s} D^{n_d} H^{n_h} N_i I\eta\rangle = (S^\dagger)^{n_s}(D^\dagger)^{n_d}(H^\dagger)^{n_h} N_i^\dagger \, |-\rangle \, , \tag{5}$$

where I and η are the same as before, and $n_s+n_d+n_h+1$ gives half the number of valence neutron holes or proton particles. Here, the N_1 and N_2 pairs are used for neutrons, and the N_3 pair, for protons. For the single-particle energies and the interaction strengths, we have used the same values as used in the previous study of ^{132}Ba [4].

The theoretical energy levels of the negative parity states are compared with the experimental data in Fig. 1. Our calculation reproduces the correct positions and ordering of the five low-lying states of 4_1^-, 5_1^-, 6_1^-, 6_2^- and 7_1^- [panel (a)]. For the other negative-parity states up to spin 9, relative positions of their energy levels are in good agreement with the observation. These results indicate that the new version of the PTSM is a useful tool to describe the low-lying states, including negative parity states.

Concerning high-spin states, the observed $\Delta I = 1$ band starting from 11^- is assigned to be built on the $\nu(h_{11/2}^2) \otimes \pi(h_{11/2} g_{7/2})$ configuration [9]. This $\Delta I = 1$ band is predicted to be a magnetic dipole band. The theoretical $\Delta I = 1$ band with the bandhead state of 13^- having large $M1$ transitions appears somewhat higher in energy than experiment, but the level spacings with spins greater than 15 are close to the observation [panel (b)]. From the results of the expectation numbers of pairs (results not shown), it is found that this $\Delta I = 1$ band is built on the pure $\nu(h_{11/2}^2) \otimes \pi(h_{11/2} g_{7/2})$ configuration. The spin of this bandhead state can be explained by the almost perpendicular angular momentum coupling of the neutron $(h_{11/2}^2)$ pair (H pair) and the proton $(h_{11/2} g_{7/2})$ pair (N_3 pair). The maximum angular momentum of the neutron H pair is equal to 10, and that of the proton N_3 pair is equal to 9. From simple geometrical considerations, it is found that the bandhead state of 13^- is constructed from perpendicular coupling of these pairs. In Fig. 2(a), the calculated $B(M1; I \to I-1)$ values of the magnetic dipole band are shown as functions of spin I.

The effective angle between two angular momenta of valence neutrons and protons θ is defined as

$$\cos\theta = \frac{\langle \Phi(I\eta)| \, \boldsymbol{I}_\nu \cdot \boldsymbol{I}_\pi \, |\Phi(I\eta)\rangle}{\sqrt{\langle \Phi(I\eta)| \, \boldsymbol{I}_\nu^2 \, |\Phi(I\eta)\rangle \, \langle \Phi(I\eta)| \, \boldsymbol{I}_\pi^2 \, |\Phi(I\eta)\rangle}}, \tag{6}$$

where $|\Phi(I\eta)\rangle$ is the even-even nuclear state, and the operator $\boldsymbol{I}_\tau$ ($\tau = \nu$ or π) stands for the angular momentum operator of the nucleons. In Fig. 2(b), the effective angles θ for the magnetic dipole band are shown as functions of spin I. For the 14^- state, two angular momenta of valence neutrons and protons are approximately perpendicular to one another. It is seen that the effective angles θ decrease monotonously as spin I increases up to spin 19. This situation is very similar to that of the shears mechanism. In this picture, valence protons and neutrons couple to form two angular momenta, adding up to make a total spin I of the nuclear states. In the lowest energy state, two angular momenta are approximately perpendicular to each other, and higher energy states are made by their closing.

In Fig. 2(c), the squares of angular momenta for valence neutrons and protons $\langle \boldsymbol{I}_\tau^2 \rangle = \langle \Phi(I\eta)|\, \boldsymbol{I}_\tau^2 \,|\Phi(I\eta)\rangle$ are plotted as functions of the spin I. The theoretical result exhibits sudden changes of the values of $\langle \boldsymbol{I}_\tau^2 \rangle$ between the 15^- and the 16^- states for both neutrons and protons. It indicates that the nuclear structure drastically changes for these states. Furthermore, the analysis of the expectation numbers of D pairs (results not shown) indicates that the effect of collective rotation is not dominant in the high-spin states ($I \geq 15$).

4. Summary

In conclusion, we have proposed a new version of the PTSM which includes negative parity pairs, and applied this model to ^{132}Ba. Our theoretical result describes well the energy levels of the low-lying negative parity states with spins between 4^- and 9^-. Concerning high spin states, a good correspondence with experiment is achieved for the energy levels of the magnetic dipole band with the $\nu(h_{11/2}^2) \otimes \pi(h_{11/2}g_{7/2})$ configuration. From analysis of its structure, it turns out that two angular momenta of valence neutrons and protons gradually close as spin I increases. However, the sudden change in the values of $\langle \boldsymbol{I}_\tau^2 \rangle$ around spin 15 indicates that the magnetic dipole band is more complicated in structure than that described by the shears mechanism. Further experimental spin-assignment investigations of the magnetic dipole bands are needed in order to understand its structure.

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