Magnetic Rotation in ^{84}Rb Postprint

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Abstract

High-spin states in 84Rb have been studied by using the 70Zn(18O, p3n)84Rb reaction at beam energy of 75 MeV. Three regular magnetic dipole bands including strong M1 and weak E2 transitions have been observed in this nucleus which shows the characteristic feature of magnetic rotation. These bands are interpreted in the projected shell model for the first time on the basis of the four-quasiparticle configuration of the type π(fp) π(g9/22) (g9/2). It is shown that the calculated sequence lies roughly in the same energy range as the experimental one but the interval between neighboring levels is larger than the corresponding experimental value. We believe that a 4-quasiparticle band crossing with the 2-quasiparticle band will depress the energies of the states.

Full Text

Preamble

Magnetic Rotation in Rubidium-84

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Abstract
High-spin states in ^{84}Rb have been studied using the ^{70}Zn(^{18}O, p3n)^{84}Rb reaction at a beam energy of 75 MeV. Three regular magnetic dipole bands featuring strong M1 and weak E2 transitions have been observed in this nucleus, demonstrating the characteristic features of magnetic rotation. These bands are interpreted for the first time within the projected shell model on the basis of a four-quasiparticle configuration of the type $\pi(g_9/_2)^2$ $(g_9/_2)^{-1}$. The calculations show that the predicted level sequence lies roughly in the same energy range as the experimental one, though the interval between neighboring levels is larger than the corresponding experimental values. We believe that a four-quasiparticle band crossing with a two-quasiparticle band will depress the energies of the states.

Key words
In-beam γ-spectroscopy, Magnetic dipole band, Projected shell model

Introduction

Magnetic rotation represents a novel mode of nuclear rotation that has attracted considerable interest in recent years. The levels of rotational bands are linked by strong magnetic dipole (M1) transitions, whereas crossover electric quadrupole (E2) transitions are very weak, resulting in large B(M1)/B(E2) ratios. This magnetic character is clearly demonstrated by the transition probability ratios for each level in the band.

Experimental evidence for magnetic rotational bands includes the observation of intense ΔI = 1 M1 transitions between neighboring levels within a band in nuclei with small deformation. These M1 transitions differ from those typically observed in high-spin states in several respects. First, the transition energies are very regular, showing no signature splitting, similar to high-K rotational bands in well-deformed nuclei. Second, the magnetic dipole reduced transition probabilities B(M1) are greatly enhanced, reaching several $\_N^2$ units, and the B(M1)/B(E2) ratios are very large. The E2 transitions within the band are extremely weak or unobservable, which distinguishes these structures from high-K bands in well-deformed nuclei. Moreover, the ratio of the dynamic moment of inertia $J^{(2)}$ to the electric quadrupole reduced transition probability B(E2) is larger than that of normal-deformation and superdeformed bands, often by as much as a factor of ten.

In recent years, magnetic rotational bands have been extensively studied both theoretically and experimentally. Initially, such bands were discovered in nuclei of the Pb region (e.g., ^{199}Pb, ^{200}Pb), around the A 140 mass region (e.g., ^{139}Sm), the A 110 region (e.g., ^{110}Cd, ^{105}Sn), and the A 80 region (e.g., ^{82}Rb and ^{84}Rb). Theoretically, various shell-model calculations and relativistic mean-field (RMF) descriptions of the shears band mechanism in ^{84}Rb were completed in this mass region about ten years ago, while the adjacent nucleus ^{82}Rb was studied using the complex Excited Vampir approach. The present work focuses on the magnetic dipole band in ^{84}Rb and complements our preceding publication.

2 Assignment of Magnetic Dipole Bands

High-spin states in ^{84}Rb were investigated via the heavy-ion fusion-evaporation reaction ^{70}Zn(^{18}O, p3n)^{84}Rb using an ^{18}O beam from the tandem accelerator at the China Institute of Atomic Energy (CIAE). Experimental procedures and results were detailed in Ref. [7], where negative-parity bands were significantly extended from the previous (6^-) state up to the highest (17^-) state, with spins and parities tentatively assigned based on γ-γ directional correlations of oriented states (DCO) ratios [8]. The γ-coincidence data were analyzed using the Radware software package [9]. In this work, we concentrate on the most striking feature: the sudden emergence of a regular magnetic dipole band at an excitation energy around 3 MeV [7].

Among the three observed bands (designated C, D, and E), band C was the first to be identified as a magnetic rotational band. It consists of seven strong M1 transitions with energies of 325, 444, 546, 655, 721, 765, and 874 keV built upon the Iˆπ = (10^-) level at E_x = 3.339 MeV. The dipole character of these transitions has been established through γ-γ DCO ratios, and M1 multipolarity is suggested by analogy to multiparticle excitations in neighboring nuclei. Analysis of its Routhian reveals no signature splitting. Although the B(M1)/B(E2) ratios could be extracted, the uncertainties are relatively large due to the weakness of the E2 transitions; nevertheless, the trend of these ratios can be determined. These experimental observations collectively demonstrate the magnetic rotational character of this band. No E2 crossover transitions are observed in bands D and E, which are also identified as magnetic rotational bands.

3 Calculations

Magnetic dipole bands (so-called shears bands) are normally described within the tilted-axis-cranking (TAC) model [10]. An important question is whether shell-model calculations can reproduce the regular M1 bands discussed above. In the present work, we investigate the regular negative-parity M1 bands in ^{84}Rb within the projected shell model (PSM) for the first time, using the lowest-lying four-quasiparticle (4qp) configuration $\pi(g_9/_2)^2$ $(g_9/_2)^{-1}$ with negative parity, as adopted from Ref. [2]. In recent years, the PSM has proven highly successful in describing a broad range of properties of deformed nuclei across the nuclear chart, with its most remarkable feature being the ability to reproduce fine details of high-spin spectroscopic data within simple physical pictures [11].

The PSM [12-15] employed in this work is a microscopic theory that solves many-nucleon systems fully quantum mechanically. The ansatz for the angular-momentum-projected wave function is given by:

$$|\psi\rangle = \sum_K f_K \hat{P}^I_{MK} |\varphi_K\rangle$$

where K labels the basis states and $\hat{P}^I_{MK}$ is the angular-momentum projection operator explicitly defined in Ref. [12]. Acting on an intrinsic state $|\varphi_K\rangle$, this operator generates states of good angular momentum, thereby restoring the rotational symmetry broken by the deformed mean field. The new shell-model basis is constructed through diagonalization of the Hamiltonian. The basis states $|\varphi_K\rangle$ are spanned by the set:

$$\{a_n^\dagger a_p^\dagger |0\rangle\}$$

for doubly odd nuclei, where $|0\rangle$ denotes the quasiparticle vacuum state and $a_n^\dagger$ ($a_p^\dagger$) is the neutron (proton) quasiparticle creation operator. The index n(p) runs over selected neutron (proton) quasiparticle states, and K in Eq. (1) runs over the configurations of Eq. (3). The vacuum state is obtained by diagonalizing a deformed Nilsson Hamiltonian [16] followed by a BCS calculation. In our calculations, we employ three major shells (N = 2, 3, and 4) for both neutrons and protons as the configuration space.

The Hamiltonian used in this work [15] is:

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_\mu \hat{Q}^\dagger_\mu \hat{Q}_\mu - G_M \hat{P}^\dagger \hat{P} - G_Q \hat{P}^\dagger_2 \hat{P}_2$$

where $\hat{H}_0$ is the spherical single-particle shell model Hamiltonian, $\hat{Q}_\mu$ is the quadrupole moment operator, and $\hat{P}^\dagger$ and $\hat{P}^\dagger_2$ are the monopole and quadrupole pairing operators, respectively. While the theory itself is not restricted to any particular Hamiltonian form, such a separable-force Hamiltonian offers the advantage that the role of each interaction term is well understood, facilitating interpretation of numerical results.

The interaction strengths are determined as follows. The quadrupole-quadrupole interaction strength is adjusted via the self-consistency condition that the input quadrupole deformation $_2$ coincides with that resulting from the HFB (Hartree-Fock-Bogolyubov) procedure [15]. The monopole pairing strength constant G_M is adjusted to reproduce the known energy gap:

$$G_M^{n,p} = \frac{21.24 \mp 13.86\frac{N-Z}{A}}{A}$$

where the minus sign applies to neutrons and the plus sign to protons. Finally, the quadrupole pairing strength G_Q is assumed proportional to G_M:

$$G_Q = 0.20G_M$$

with the proportionality constant chosen as 0.20 for all bands calculated in this work.

In the calculations performed by Schnare et al. [2-4], the lowest-lying 4qp configuration for Z = 37 and N = 47 is $\pi(g_9/_2)^2 \quad (g_9/_2)^{-1}$. This negative-parity configuration is consistent with our experimental findings. The "shears" mechanism is generated by two protons in the $g_9/_2$ orbital and one unpaired $g_9/_2$ neutron. Following our recent study of the negative-parity yrast band in this nucleus [7], we construct the configuration space for the magnetic dipole band calculations in ^{84}Rb by selecting quasiparticle states near the Fermi energy in the N = 4 (neutron) and N = 3 (proton) major shells: specifically, the K = 7/2 orbital of the $g_9/_2$ subshell for neutrons and all orbitals of the $p_3/_2$ and $f_5/_2$ subshells for protons to form multi-qp states. The quadrupole deformation parameter $_2 = 0.14$ is adopted from Ref. [2], and the hexadecapole deformation parameter $_4 = 0.007$ is taken from the compilation of Möller et al. [17].

The calculated level energies for the resulting level sequences are presented in Figs. 1, 2, and 3, respectively, and compared with experimental results from our work (see Fig. 2 of Ref. [7]). The figures show that the ordering of experimental states is well reproduced and the calculations predict roughly the correct energy range for the experimental M1 band. However, Fig. 1 reveals that the calculated 12^- to 17^- states lie above their experimental counterparts, in contrast to the lower-spin 10^- and 11^- states. This discrepancy likely arises because a two-quasiparticle (2qp) configuration was adopted in our calculations instead of the full 4qp configuration, meaning the alignment of a $g_9/_2$ proton pair has not yet been considered. Such alignment would lower the level energies. Additionally, inclusion of the triaxial deformation parameter γ [2] would also reduce the calculated energies [18].

In the present work, the characteristics of the three dipole bands shown in Figs. 1-3 are compared with the general criteria for an MR band, where level energies (E) and spins (I) follow the relation:

$$E - E_0 = A_0(I - I_0)^2$$

with E_0 and I_0 representing the energy and spin of the bandhead, respectively, and A_0 being a constant. We plot E - E_0 versus (I - $I_0)^2$ in Figs. 4a, 4b, and 4c for bands C, D, and E, respectively. The solid lines represent fits to the data using Eq. (7). The excellent agreement between data and fitted curves demonstrates that bands C, D, and E all obey the relation in Eq. (7). The dynamic moments of inertia $J^{(2)}$ obtained for the three bands using:

$$J^{(2)}(I) \approx 2/A_0$$

fall within the typical range $J^{(2)}$ 10-25 $\hbar^2$ MeV^{-1} for MR bands. Therefore, we conclude that each of these three bands most likely represents a magnetic rotational band.

4 Conclusion

High-spin states in ^{84}Rb were populated via the ^{18}O + ^{70}Zn reaction at a beam energy of 75 MeV. Three negative-parity M1 sequences have been observed in the doubly odd nucleus ^{84}Rb, exhibiting characteristic features of magnetic rotation such as regular level spacings and large B(M1)/B(E2) probability ratios. The ordering of experimental states is well reproduced by projected shell model calculations based on the four-quasiparticle configuration $\pi(g_{9}/_{2})^2$ $(g_{9}/_{2})^{-1}$.

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Note: Figure translations are in progress. See original paper for figures.