Excited states with Λ hyperon in p-orbit in ${}^{25}_{\Lambda}$Mg

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Abstract

The excited states of ${}^{25}_{\Lambda}$Mg with the Λ hyperon in p-orbit are studied with the antisymmetrized molecular dynamics for hypernuclei. Three rotational bands are obtained by adding Λ in p-orbit to the ground band of ^{24}Mg. It is found that these bands energetically split due to the triaxial deformation of the core nucleus ^{24}Mg and the spatial anisotropy of the p-orbits of Λ.

Keywords: Λ hypernuclear structure, triaxial deformation

1. Introduction

In this article, we focus on the hypernuclear state with the Λ hyperon in p-orbit which we call p state in the following.

Since a hyperon is unaffected by Pauli principle from nucleons, it can be regarded as an impurity in nuclei and modifies nuclear properties such as clustering and deformation. In p-shell Λ hypernuclei, experimental and theoretical studies have revealed a couple of interesting structure changes. For example, the reduction of the intercluster distance by the Λ hyperon in s-orbit has been confirmed through the observation of E2 transition probabilities $B(E2)$ in ${}^{7}_{\Lambda}$Li [1, 2, 3, 4], that has the developed $\alpha + d + \Lambda$ cluster structure. In sd-shell Λ hypernuclei, various structure changes have been predicted theoretically, because normal sd-shell nuclei have a variety of structures, such as cluster structure and mean-field like structure with axial/triaxial deformation, in the ground and low-lying states. For example, the parity inversion of the ${}^{20}_{\Lambda}$Ne ground state was predicted [5]. In ${}^{21}_{\Lambda}$Ne, it was predicted that the Λ hyperon generates various α+^{16}O +Λ cluster states and mean-field-like states [6, 7]. The difference between these structures leads to the difference in the Λ binding energies and the reduction of the $B(E2)$ [7]. It is expected that the structure changes predicted in p-sd shell Λ hypernuclei will be revealed by the forthcoming experiments at J-PARC, JLab and Mainz.

In case of the Λ hyperon in p-orbit, it can be regarded as a probe of nuclear deformation due to its spatial anisotropy. For example, in ${}^{9}_{\Lambda}$Be, the splitting of the p states was predicted due to the axial symmetric deformation (2α clustering) of ^{8}Be [8, 9]. Namely, the Λ hyperon in p-orbit generates two rotational bands in which Λ moves along the parallel and perpendicular directions of the 2α clustering, respectively [9]. In other words, the anisotropy of the p-orbit and axially symmetric deformation of ^{8}Be lead to the splitting of the p states. It is noted that the former p state of ${}^{9}_{\Lambda}$Be is known as a super-symmetric [8] (or genuine hypernuclear [9]) state, and cannot be formed in an ordinary ^{9}Be nucleus with the $\alpha + \alpha + n$ configuration, because of the Pauli exclusion principle. From this fact, we may deduce that the p states will split into three in the case of triaxial deformation, and this conjecture suggests a

challenging task, *i.e.* probing triaxial deformation of the core nucleus by the observation of three different p states in Λ hypernuclei.

^{24}Mg is one of the candidates of triaxially deformed nuclei with the presence of the low-lying 2_2^+ state [10]. Therefore, we expect that the p states of $^{25}_{\Lambda}$Mg will split into three with different spatial density distribution of Λ. So far, in case of $^{25}_{\Lambda}$Mg, structure changes caused by Λ in s orbit were investigated focusing on the triaxial deformation. For example, it was predicted that the addition of a Λ particle makes $^{25}_{\Lambda}$Mg slightly soft against γ deformation [11]. And, a Λ particle slightly stretches the ground band and reduces the intraband $B(E2)$ values in $^{25}_{\Lambda}$Mg [12]. However, structure of the p states in $^{25}_{\Lambda}$Mg has not been discussed in the past.

The aim of the present work is to reveal the splitting of the p states of $^{25}_{\Lambda}$Mg and its relation to the triaxial deformation. To study it, we have employed the antisymmetrized molecular dynamics for hypernuclei (HyperAMD). The HyperAMD with the generator coordinate method (GCM) was successfully applied to $^{25}_{\Lambda}$Mg with Λ in s-orbit in our previous work [13], in which the modifications of the excitation spectra by Λ in s-orbit associated with the triaxial deformation of ^{24}Mg was discussed. In this work, we imposed the constraint on the Λ single particle wave function, to obtain the Λ hyperon in p-orbit, as well as the nuclear quadrupole deformation in the HyperAMD calculation.

2. Framework

We have performed the HyperAMD calculation basically following our previous work [13].

The Hamiltonian used in this study is given as,

$$\hat{H} = \hat{H}_N + \hat{H}_\Lambda - \hat{T}_g, \tag{1}$$

$$\hat{H}_N = \hat{T}_N + \hat{V}_{NN} + \hat{V}_{Coul},\ \hat{H}_\Lambda = \hat{T}_\Lambda + \hat{V}_{\Lambda N}. \tag{2}$$

Here, $\hat{T}_N$, $\hat{T}_\Lambda$ and $\hat{T}_g$ are the kinetic energies of nucleons, a Λ hyperon and the center-of-mass motion, respectively. We have used the Gogny D1S as an effective nucleon-nucleon interaction $\hat{V}_{NN}$. As an effective ΛN interaction $\hat{V}_{\Lambda N}$, we have used the central force of the YNG-NSC97f [14] with Fermi momentum $k_F = 1.2$ fm^{-1}.

The intrinsic wave function of a single Λ hypernucleus composed of A nucleons and a Λ hyperon is described by the parity-projected wave function, $\Psi^\pi = \hat{P}^\pi \Psi_{int}$, where $\hat{P}^\pi$ is the parity projector. The intrinsic wave function Ψ_{int} is given as $\Psi_{int} = \Psi_N \otimes \varphi$, where Ψ_N is defined by a Slater determinant of the nucleon single particle wave packets. The Λ single particle wave function φ is represented by a superposition of Gaussian wave packets, as

$$\varphi = \sum_{m=1}^{M} c_m \phi_m(r),\ \phi_m = \prod_{\sigma=x,y,z} \left(\frac{2\nu_\sigma}{\pi}\right)^{\frac{1}{4}} \exp\left\{-\nu_\sigma \left(r - z_m\right)_\sigma^2\right\} \chi_m, \tag{3}$$

to describe Λ in p-orbit. Here χ_m is the spin wave functions of Λ.

By using the frictional cooling method, the variation parameters are so determined as to minimize the total energy under the constraints. Two kinds of constraints are simultaneously imposed on the variational calculation. The first is imposed on nuclear quadruple deformation parameters β and γ to obtain the intrinsic wave functions of $^{25}_{\Lambda}$Mg for given deformation parameters as in our previous work [13]. The other is imposed on the Λ single particle wave function to obtain p states by adding the constraint potential, $V_f = \lambda \sum_f |\varphi_f\rangle\langle\varphi_f|$, which forbids the Λ hyperon occupying the orbit φ_f with sufficiently large value of λ. The actual calculational procedure is as follows. First, we perform the variational calculation with constraint on the nuclear deformation but without the constraint on the Λ single particle wave function to obtain the lowest energy state of $^{25}_{\Lambda}$Mg for given values of β and γ. Then, denoting the Λ single particle s-orbit obtained by this calculation as φ_1, we perform another variational calculation with the second constraint, $V_f = \lambda|\varphi_1\rangle\langle\varphi_1|$, as well as the constraint on the nuclear deformation. This variational calculation generates second lowest energy state whose Λ single particle wave function is denoted as φ_2, and we complete the calculation for the s-orbit states having two different spin directions. We further proceed the calculation by adding the constraint $V_f = \lambda \sum_{f=1,2} |\varphi_f\rangle\langle\varphi_f|$, which produces the third lowest energy state (*i.e.* the lowest p state) φ_3. By continuing this procedure, we obtain two s-orbits (φ_1 and φ_2) and six p-orbits ($\varphi_3, \cdots, \varphi_8$).

The Λ single particle energies as a function of (β, γ) which is defined as,

$$\epsilon_f(\beta,\gamma) = \langle \Psi_f^\pi(\beta,\gamma)|\hat{H}_\Lambda|\Psi_f^\pi(\beta,\gamma)\rangle,\ f = 3, 4, \cdots, 8, \tag{4}$$

are two-fold degenerated due to the small ΛN spin-orbit interaction, and hence, we obtain three p states with different spatial distribution which we denote as φ_{p1}, φ_{p2} and φ_{p3} in ascending order of their single particle energies, ϵ_{p1} $(= \epsilon_3 = \epsilon_4)$, ϵ_{p2} $(= \epsilon_5 = \epsilon_6)$ and ϵ_{p3} $(= \epsilon_7 = \epsilon_8)$.

After the variation, we performed the angular momentum projection and the generator coordinate method (GCM) calculation to obtain the excitation spectra of ${}^{25}_{\Lambda}$Mg.

3. Results and discussions

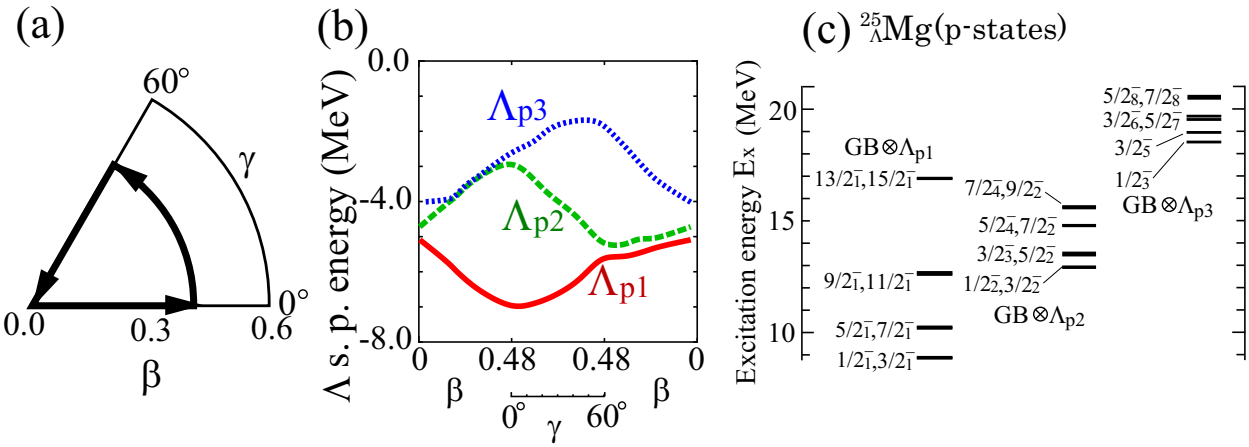

Figure 1. (b):Λ single particle energy defined by Eq. (4) for φ_{p1}, φ_{p2}, and φ_{p3} along the loop shown in (a). This loop starts from and heads back to the origin ($\beta = 0, \gamma = 0°$) via ($\beta = 0.48, \gamma = 0°$) and ($\beta = 0.48, \gamma = 60°$). (c): Excitation spectra of the p states in ${}^{25}_{\Lambda}$Mg

The dependence of the Λ single particle energies (ϵ_{p1}, ϵ_{p2} and ϵ_{p3}) on the nuclear quadruple deformation are clearly seen in Fig. 1(b), where they are plotted along the path on the (β, γ) plane shown in Fig. 1(a). In triaxially deformed region ($0° < \gamma < 60°$), the Λ single particle energies are different from each other for φ_{p1}, φ_{p3} and φ_{p3}, while two of them are degenerated with axial deformation ($\gamma = 0°$ and $\gamma = 60°$). Therefore we can expect that three p states appear in ${}^{25}_{\Lambda}$Mg. However, the above discussions neglect the energy of the nucleon part which also varies as a function of β and γ, and we need to take it into account by performing the GCM calculation.

Figure 1(c) shows the excitation spectra of the p stats in ${}^{25}_{\Lambda}$Mg, obtained with the GCM calculation. Three rotational bands are obtained as the p states of ${}^{25}_{\Lambda}$Mg corresponding to the ground band (GB) of ^{24}Mg. It is found that coupling of φ_{p1}, φ_{p2} and φ_{p3} to the ground band of ^{24}Mg generates the three bands built on the $(1/2^-_1, 3/2^-_1)$, $(1/2^-_2, 3/2^-_2)$ and $(1/2^-_3, 3/2^-_5)$ states, respectively. Therefore, the p states coupled to the ground band of ^{24}Mg split into three bands.

4. Summary

In summary, we have investigated the level structure of the p states in ${}^{25}_{\Lambda}$Mg based on the HyperAMD calculation with constraints on the Λ single particle wave function and nuclear quadrupole deformation. Combined with the angular momentum projection and the GCM calculation, we obtained the excitation spectra of the p states in ${}^{25}_{\Lambda}$Mg. It is found that Λ in p-orbit generates three rotational bands corresponding to the ground band of ^{24}Mg. Therefore the p states of ${}^{25}_{\Lambda}$Mg split into three. This is due to the triaxial deformation of the ^{24}Mg ground state. The splitting of the p states into three was not predicted in the p-shell Λ hypernuclei, because the most of the$p$-shell nuclei have the ground state with axial deformation. Observation of the splitting in ${}^{25}_{\Lambda}$Mg will be a direct evidence of the triaxial deformation of the ^{24}Mg ground state. Unfortunately, it is difficult to observe it by using the γ-ray spectroscopy, because the most of the p states lie above the lowest decay threshold α+${}^{21}_{\Lambda}$Ne. However, it may be possible to observe them through the reaction spectroscopy. Therefore, it is required to predict the production cross section of the p states in ${}^{25}_{\Lambda}$Mg and how to observe them in our future work.

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