Spin-dependence of Ξ-N interaction and Ξ hypernuclear production spectrum

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Abstract

An extended version of the Antisymmetrized Molecular Dynamics (AMD) that describes the multi-strangeness system is suggested. The strong dependence of the ${}^{12}_{\Xi}$Be ground doublet on the ΞN interaction was found and the possibility to determine the ΞN interaction from the ^{12}C$(K^+, K^-){}^{12}_{\Xi}$Be reaction is suggested. The drastic structure change of ${}^{13}_{\Lambda}$C is also discussed.

Key words:
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1. Introduction

We discuss the spin-dependence of ΞN interaction which may be determined from the Ξ hypernuclear formation spectra measured in the day-one experiment at J-PARC [1]. Ξ hypernuclei provide essential information on BB interaction and dense matter. To investigate the nature of the ΞN interaction and the structure of the Ξ hypernuclei, we have developed an extended version of AMD called ccAMD. Based on ccAMD, the low-lying level structure and the production spectrum of ${}^{12}_{\Xi}$Be are investigated. We suggest the possibility to determine the spin-dependence of ΞN interaction from the experiment. The ccAMD is also applied to the Λ hypernuclei and the drastic change of the deformation in ${}^{13}_{\Lambda}$ C is discussed.

2. Theoretical Framework of ccAMD

The Hamiltonian used in this study is given as,

$$\hat{H} = \sum_i \hat{t}_i - \hat{t}_{CM} + \frac{1}{2}\sum_{i\neq j} \hat{v}^{NN}_{ij} + \frac{1}{2}\sum_{i\neq j} \hat{v}^{YN}_{ij} + \Delta M, \tag{1}$$

where $\hat{t}_i$, $\hat{t}_{CM}$ and ΔM stand for the single particle and center-of-mass kinetic energies, and the mass difference between baryons in each channel. In the study of the Ξ hypernuclei, we have used the BBO1 [2] and the spin-orbit part of the G3RS [3] as the effective nucleon-nucleon interaction $\hat{v}^{NN}$. Three different effective interactions (the central part of the G-matrix interaction derived from ESC04d, Ehime and NHC-D) are used as the effective Ξ-N interactions [4] to study the interaction dependence of the spectroscopy of the Ξ hypernuclei.

In the study of the Λ hypernuclei, we have used the Gogny D1S interaction as $\hat{v}^{NN}$. The YNG-ND interaction has been employed as the Λ-nucleon interaction. The YN interactions used in this study have the k_F dependence and its value is determined in the self-consistent way.

The ccAMD employs the parity projected coupled-channel wave function $\Psi^{\pm}$ as the variational wave function,

$$\Psi^{\pm} = \sum_a c_a \hat{P}^{\pm}\Phi^a, \tag{2}$$

where the suffix a represents each baryon channel under the consideration and the coefficients c_a mix these channels. In the present study, we have included two channels, $^{11}\mathrm{B}\otimes\Xi^0$ and $^{11}\mathrm{Be}\otimes\Xi^-$ to describe $^{12}_{\Xi}\mathrm{Be}$. The Λ nuclei are studied by the single channel calculation. Each baryon channel is represented by a parity projected Slater determinant of the baryon single particle wave packets. And each wave packet are factorized into the spatial part with Gaussian form ϕ^a_i, spin χ^a_i and flavor ξ^a_i parts,

$$\Phi^a = \frac{1}{\sqrt{A!}}\det\{\varphi^a_i\}, \quad \varphi^a_i(\boldsymbol{r}) = \phi^a_i(\boldsymbol{r})\cdot\chi^a_i\cdot\xi^a_i, \tag{3}$$

$$\phi^a_i(\boldsymbol{r}) = \left(\frac{2\nu}{\pi}\right)^{3/4}\exp\left\{-\nu\left(\boldsymbol{r}-\frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2\right\}, \tag{4}$$

$$\chi^a_i = \alpha^a_i\chi_{\uparrow} + \beta^a_i\chi_{\downarrow}, \quad \xi^a_i = \text{baryon octet } (p, n, \Lambda, \Xi^- \text{or } \Xi^0, ...). \tag{5}$$

The mixing between channels c_α, the centroid and width of the Gaussians $\boldsymbol{Z}^a_i$, ν and the direction of the spins α^a_i, β^a_i are the variational parameters. They are so determined that the energy of the system is minimized.

After the variational calculation, we perform the angular momentum projection and the generator coordinate method (GCM).

$$\Psi^{J\pm}_{Kb} = \hat{P}^J_{MK}\Psi^{\pm}_b, \quad \Psi^{J\pm}_\alpha = \sum_{K,b} d^\alpha_{Kb}\Psi^{J\pm}_{Kb}. \tag{6}$$

Here, $\hat{P}^J_{MK}$ is the angular momentum projector. $\Psi^{\pm}_{Kb}$ denotes the wave functions obtained through the coupled-channel frictional cooling equation. They have various nucleon and hyperon configurations and are superposed to describe the hypernuclear state $\Psi^{J\pm}_\alpha$. The coefficients d^α_{Kb} is determined by the Hill-Wheeler equation,

$$H_{ij}d^\alpha_j = E_\alpha N_{ij}d^\alpha_j, \quad H_{ij} = \langle\Psi^{J\pm}_{Kb}|\hat{H}|\Psi^{J\pm}_{K'b'}\rangle, \quad H_{ij} = \langle\Psi^{J\pm}_{Kb}|\Psi^{J\pm}_{K'b'}\rangle, \quad i=\{K,b\},\ j=\{K',b'\}. \tag{7}$$

The production spectrum of the Ξ hypernuclei is calculated within the plane wave impulse approximation by using the hypernuclear and normal nuclear wave functions obtained by the calculational procedure described above.

3. Spectroscopy and production of Ξ hypernuclei

Figure 3 shows the low-lying level schemes obtained by using the ESC04d, Ehime and NHC-D interactions. The binding energies of Ξ^- hyperon B_Ξ are 5.5 (ESC04d), 3.1 (NHC-D) and 3.3 (Ehime) MeV. We have found that the low-lying states of $^{12}_{\Xi}\mathrm{Be}$ are dominated by the $^{11}\mathrm{B}\otimes\Xi^-$ channel. The $^{11}\mathrm{Be}\otimes\Xi^0$ channel mainly contributes to the excited states lying more than 6MeV above the ground state and the mixing between two channels is rather weak. The ground doublet (2^-_1 and 1^-_1 states) is dominated by the $^{11}\mathrm{B(g.s.)}\otimes s_\Xi$ configurations in which $^{11}\mathrm{B}$ and hyperon spins are aligned in parallel and antiparallel. Their order and splitting width are different for

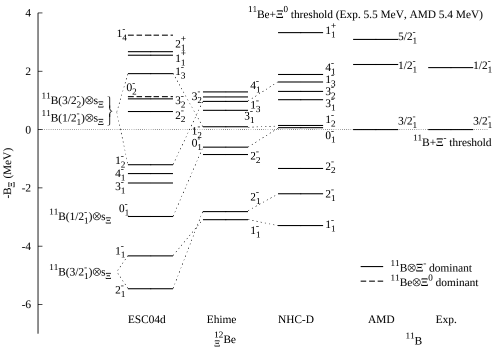

Figure 1: Low-lying spectrum of $^{12}_{\Xi}$Be. Solid (dashed) lines show the states dominated by the ^{11}B$\otimes\Xi^-$ (^{11}Be$\otimes\Xi^0$) channels.

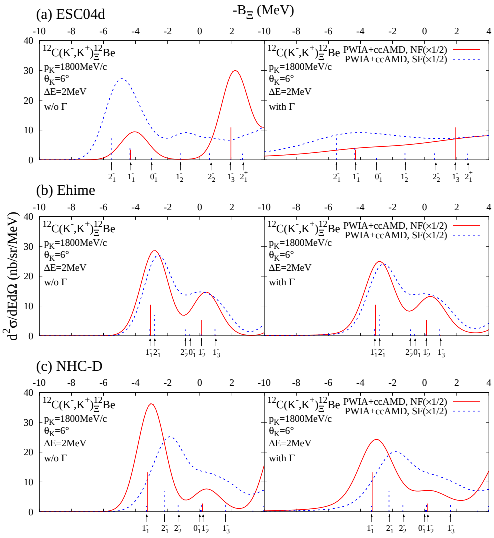

Figure 2: Low-lying spectrum of $^{12}_{\Xi}$Be. Solid (dashed) lines show the states dominated by the ^{11}B$\otimes\Xi^-$ (^{11}Be$\otimes\Xi^0$) channels.

each interaction and quite sensitive to the strength of the spin-spin part. The ESC04d has the strong attraction in the spin-triplet channel and it makes the 2^-_1 state the ground state. On the contrary, the NHC-D is repulsive and the 1^-_1 state becomes the ground state. The Ehime has the weaker repulsion and the splitting width is smaller than the NHC-D.

The calculated spectroscopic factors show that the excited state except for the 0^-_1 has the strong mixing of the various core excited states, even though the excitation energy is not large. Therefore, the relation between their order and nature of the effective interactions is not so clear as in the ground doublet. It is also noted that the Λ hypernuclei also have the strong mixing of the core excited states. For example, the present calculation nicely reproduces the observed small peaks of the ^{12}C(π^+,K^+)$^{12}_{\Lambda}$C reaction that originates in the core excited states.

Nature of each ΞN interaction is strongly reflected to the spectrum by the ^{12}C(K^-,K^+)$^{12}_{\Xi}$Be reaction as presented in Figure **??**. Since the spin dependence of the elementary process $pK^- \to \Xi^- K^+$ is unknown, we have separated the spectrum into the spin-flip (dashed) and non-flip (solid) components. In the left panel, the conversion width into the $\Lambda\Lambda$ channel is estimated from the imaginary part of the effective interaction, while it is neglected in the right panel. The observation of the $^{12}_{\Xi}$Be bound state as the discrete peak looks hopeful in the case of the NHC-D and Ehime. However, in the case of the ESC04d, its large imaginary potential washes out the bound discrete peaks. Aside from the conversion width, it must be noted that the pattern of the spin-flip and non-flip spectrum is quite sensitive to the effective interaction. In the case of the ESC04d, the spin-flip spectrum has its peak at lower energy than the non-flip spectrum, while the NHC-D shows the opposite pattern . It clearly depends on whether the ground state of $^{12}_{\Xi}$Be is dominated by the spin-triplet configuration or not. This means that it is possible to determine the sign of the spin-spin part of the ΞN interaction from the observation of ^{12}C(K^-,K^+)$^{12}_{\Xi}$Be reaction. Practically, it requires the knowledge of the spin dependence of the elementary process and to control the ratio of spin-flip and non-flip process, for example, by changing the detector angle or incident energy.

4. Impurity effects caused by Λ hyperon

In the normal *sd*-shell nuclei, the shell and cluster structure coexist within very small excitation energy. Therefore, we can expect the drastic structure change caused by the Λ particle as a novel and interesting phenomenon peculiar to *sd*-shell hypernuclei. Here, we demonstrate such structure change of ${}^{13}_{\Lambda}$C and ${}^{20}_{\Lambda}$Ne.

Figure **??** shows the potential energy surfaces for ${}^{13}_{\Lambda}$C as function of the quadrupole deformation parameter β compared with the normal nuclei ^{12}C. ^{12}C has the oblately deformed ground state associated with the 3α clustering. The addition of Λ particle in *s*-shell reduces the quadrupole deformation and the ground state of ${}^{13}_{\Lambda}$C is spherical. On the contrary, the Λ particle in *p*-shell enlarges the deformation. This change comes from the the Nilsson orbital-like behavior of the Λ single particle orbital. It is also noted that the internal spin of nuclear part is not saturated and it changes from the jj-coupling to the LS-coupling scheme as deformation becomes larger. Therefore, the internal spin of the nuclear part is not negligible in the discussion of the spin-orbit splitting of ${}^{13}_{\Lambda}$C and the structure change caused by Λ particle will have considerable influence on it.

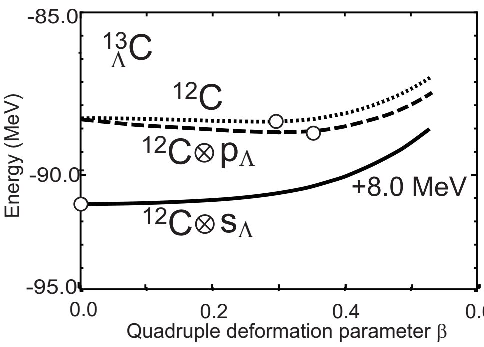

Figure 3: Energy surface of ${}^{13}_{\Lambda}$C as function of matter quadrupole deformation β.

5. Summary

To summarize, we have developed an extended version of the Antisymmetrized Molecular Dynamics that describes the system with the multi-strangeness. It enables the quantitative study of the *sd*-shell hypernuclei. By using three different effective ΞN interactions, we have found that ${}^{12}_{\Xi}$Be is bound deep enough and descrete bound peak appears in the case of the NHC-D and Ehime, while the ESC04d results in the broad spectrum. The calculate spectrum also suggests the possibility to determine the sign of the spin-spin part of ΞN interaction. We also demonstrated the drastic structure change of ${}^{13}_{\Lambda}$C. Not only the deformation but also the internal spin of the nuclear part is modified by adding the Λ particle.

References

[1] J-PARC E05, T. Nagae, et. al.
[2] A. Isshiki, K. Naito and A. Ohnishi, Prog. Theor. Phys. **114**, 573 (2004).
[3] R. Tamagaki, Prog. Theor. Phys. **39**, 91 (1968).
[4] Th. A. Rijkenand and Y.Yamamoto,arXiv:nucl-th/0608074; M. Yamaguchietal., Theor.Phys. **105** (2001),627.; M. M. Nagelsetal., Phys. Rev. **D15** (1977),2547.