Di-neutron correlations and their dependence on coupling to continuum

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Abstract. We investigate the two-neutron correlations in ⁶He and ¹¹Li nuclei through the density distributions of the valence neutrons. In this work, we use the two-neutron wave functions for halo nuclei within the extended three-cluster model assuming the core+⁷+n structures, where the internal correlations in the core nucleus are taken into account. For the ⁶He nucleus, the mixing of higher partial waves increases the spin singlet states slightly and enhances the di-neutron correlations. For the ¹¹Li nucleus, a large s-wave mixing suppressed to form the spin triplet states and the di-neutron correlations are dramatically enhanced by the large amount of the singlet states.

1. Introduction

Recent developments of RI beam experiments have discovered the new and exotic nuclear structures. As one of such interesting structures, the halo structures in ⁶He and ¹¹Li nuclei have been studied theoretically by using the core+n+n three-cluster models. [1-6] The appearances of the halo structures in the Borromean systems such as ⁶He and ¹¹Li have been understood as the results from the spatially-extended valence two-neutron above the core. [7] However, the understanding on the two-neutron correlation and the core-n correlation bringing the halo structure has not been established yet.

In this report, we focus our main interest on the two-neutron correlations, and discuss the difference between ⁶He and ¹¹Li nuclei from the viewpoint of partial wave mixing of single particle orbits for the valence neutron. The pairing correlation between valence neutrons has been studied, and it has been shown that such a correlation plays an important role in the binding mechanism of the Borromean systems such as ⁶He and ¹¹Li. [2,4,6] Due to the pairing correlation, single particle orbits of the neutron are mixed up to extraordinarily-higher angular momenta. [3,6] This is a common property in both ⁶He and ¹¹Li nuclei. On the other hand, in ¹¹Li nuclei, the violation of the N = 8 magic number has been observed, [8] and a large s-wave component for the valence neutrons was suggested experimentally. However, the large s-wave mixing due to the violation of neutron magic number does not occur in ⁶He nuclei, and hence the effect of the large s-wave mixing in ¹¹Li is a problem in discussing the difference of the two-neutron correlation between ⁶He and ¹¹Li. We here investigate the two-neutron correlations on the basis of facts that neutron orbits are mixed up to the extraordinarily-higher partial waves and the large s-wave component is mixed in the ¹¹Li nucleus.
In the following sections, we investigate the two-neutron correlations through the density distributions for valence neutrons using the extended core+n+n three-cluster model. The brief explanation of the present model and the definition of the two-neutron density distributions will be given in section 2. In section 3, we will show the results of the density distributions for $^6\text{He}$ and $^{11}\text{Li}$ and discuss the effect of the higher partial wave mixing. Finally, in section 4, all results and discussions will be summarized.

2. Two-neutron density distributions for valence neutrons in halo nuclei

2.1. Core+n+n three-cluster model for $^6\text{He}$ and $^{11}\text{Li}$ nuclei

In this report, we employ the extended core+n+n three-cluster model. [2,4,6] The total Hamiltonian is given as

$$\mathcal{H} = h_C + \sum_{i=1}^{3} t_i - T_G + V_{n-n} + \sum_{i=1}^{2} V_{\text{core-n}}(r_i) + \lambda |\phi_{\text{PF}}\rangle \langle \phi_{\text{PF}}|,$$

(1)

where $h_C$ is the intrinsic Hamiltonian for the core nucleus, and $t_i$ and $T_G$ are the kinetic energies of each cluster and the center of mass of the three-body system, respectively. The details of $h_C$ are given in Refs. 9 and 10 and skipped here. We use the Minnesota force ($^6\text{He}$) and the AV8' force ($^{11}\text{Li}$) for $V_{n-n}$, where the exchange-mixture parameter of the Minnesota force is taken as 0.95. For $V_{\text{core-n}}$, we use the KKNN potential and the folded modified Hasegawa-Nagata potential for $^6\text{He}$ and $^{11}\text{Li}$ nuclei, respectively. The Pauli principle between the core and valence neutrons is taken into account by using the pseudo potential $\lambda |\phi_{\text{PF}}\rangle \langle \phi_{\text{PF}}|$, which removes the Pauli forbidden states from the core-n relative motion, and $\lambda$ is taken as $10^6$ MeV for every calculation.

In addition, to discuss the effect of the partial wave mixing, we employ the hybrid-TV model.[2,4] In this model, the basis functions are expanded on the cluster orbital shell model (COSM; V-type), which presents a $j$-$j$ coupling scheme, and the extended cluster model (ECM; T-type), which presents an $L$-$S$ coupling scheme. By including the ECM bases, we describe the two-neutron correlation explicitly, and take the higher partial wave components into the model space. [2,4,6] For the large $s$-wave mixing in $^{11}\text{Li}$, we employ the tensor optimized shell model (TOSM) for the $^9\text{Li}$ core. [10] Considering the pairing and tensor correlations in the $^9\text{Li}$ core, Myo et al. obtain the reasonable agreement with the experimental data on the $s$-wave component, and we use their wave function for the present calculations.

2.2. Density function for valence neutrons

To analyze the two-neutron correlation, we define the density function for two valence neutrons as

$$\rho(r, \theta) = \langle \Phi_{g.s.}(r_1, r_2, \theta_{12}) | \delta(r_1 - r) \delta(\theta_{12} - \theta) | \Phi_{g.s.}(r_1, r_2, \theta_{12}) \rangle,$$

(2)

where $\Phi_{g.s.}(r_1, r_2, \theta_{12})$ is the wave function of the ground state for $^6\text{He}$ or $^{11}\text{Li}$ nuclei. The wave function is defined as the function of three parameters: The lengths, $r_1$ and $r_2$, between the core and each neutron and the opening angle $\theta_{12}$. This density function is given by integrating over $r_2$ with a weight of $8\pi^2 r_1^2 r_2^2 \sin \theta_{12}$, and normalized as

$$\int_0^\infty \int_0^\pi dr d\theta \rho(r, \theta) = 1.$$

(3)

3. Analysis of two-neutron correlations

3.1. Density distributions and effects of higher partial wave mixing in $^6\text{He}$

We first determine the effect of higher partial wave mixing in the case of $^6\text{He}$ by comparison between following two results: One is the result of two-neutron density distributions of $^6\text{He}$ with
Figure 1. The two-neutron density distribution of $^6$He calculated with the $\alpha+n+n$ hybrid-TV model. The top panel shows the total density defined by Eq. (2), and the middle and the bottom panels show the $S=0$ and the $S=1$ components, respectively.

Figure 2. The two-neutron density distribution of $^6$He as Fig. 1. In this calculation, we limit the configuration of two valence neutrons as $(0p_{3/2})^2$.

The hybrid-TV model as shown in Fig. 1, where much higher partial waves are mixed by including the ECM bases in the hybrid-TV model. Another is the result of the $(0p_{3/2})^2$ configuration for valence neutrons as shown in Fig. 2. We here introduce the $\alpha+n+n$ three-body interactions [11] in each calculation to reproduce the binding energy and radius of the $^6$He nucleus rather than including the effect of the internal correlations of the core nucleus, on the assumption that the core excitation effect is small enough to be treated as a perturbation.

In both results, the density distributions have two-peaked structures and such structures appear in the spin singlet states mainly. On the other hand, compared with Fig. 2, the result of Fig. 1 shows the enhancement of the two-neutron correlation localized spatially, that is the so-called di-neutron, and this enhancement must be the effect of higher partial wave mixing. The mixing of higher partial wave components enhances the possibility to form the spin singlet state of neutron pair slightly, and then two valence neutrons localize to gain the interaction energy. In $^6$He, due to the weak attractive force between two neutrons in the $^4S_0$ channel, the localization of two neutrons in the singlet state is realized partially, and di-neutron correlation is enhanced as shown in Fig. 1.
3.2. Density distributions and effects of the large s-wave mixing in $^{11}$Li

We investigate the dependence of the two-neutron correlation on the s-wave mixing in the case of $^{11}$Li. In order to see the s-wave dependence of the density distributions, we employ two types of $^{11}$Li wave functions, being with a large or a small s-wave component. One is the wave function presented by Myo et al. [9], where the Pauli blocking effect has an influence on the p-wave neutron due to the tensor correlation in the $^9$Li core and the amount of the s-wave mixing is reproduced in good agreement with the experimental data, and its s-wave component value is 46.9 %. Another is the wave function expected in the ordinary core+$n+n$ three-cluster model assuming the inert core, and it does not reproduce the observed value of the s-wave component. The s-wave component value for this wave function is 4.3 %.

We show the obtained two-neutron density distributions using the above two types of wave functions in Figs. 3 and 4. In both results, the enhancement of the di-neutron correlation in the spin singlet state occurs, which comes from the higher partial wave mixing, as same as the case of $^6$He. However, the total distributions in Figs. 3 and 4 are clearly different from each other. This difference in the shapes of total distributions is mainly caused by the ratio of the spin singlet state to triplet state. As increasing the s-wave component, the possibility to form the spin triplet state is suppressed and the amount of the singlet state is increased relatively.

The increase of the spin singlet state is advantageous to gain the interaction energy due to the attractive force in the $^1S_0$ channel. As a result, the di-neutron correlation is enhanced drastically by the large s-wave mixing.

By comparison with the results of $^6$He, the enhancement of the di-neutron correlation in
the $^{11}$Li nucleus indicates that the importance of the selection of the core-$n$ interaction. The possibility to form the spin singlet state has a key role in determining the two-neutron correlation, especially the di-neutron correlation, and it depends heavily on the neutron single particle orbits constructed by the core-$n$ interaction. To discuss the two-neutron correlation precisely, we must treat the core-$n$ system carefully to reproduce not only higher partial wave components but also lower ones at least.

4. Summary

We have investigated the two-neutron correlations in $^6$He and $^{11}$Li from the viewpoint of the effect of the partial wave mixing. It is found that the two-neutron correlation depends heavily on the possibility to form the spin singlet state and treatment of the core-$n$ system. In both nuclei, the higher partial wave mixing coming from the weak binding energy enhances the di-neutron correlation. For $^{11}$Li nuclei, the large $s$-wave mixing enhances the di-neutron correlations strongly.

References

[1] Danilin B V, Zhukov M V, Ershov S N, Gareev F A, Kurmanov R S, Vaagen J S and Bang J M 1991 Phys. Rev. C43 2835
[2] Tosaka Y and Suzuki Y 1990 Prog. Theor. Phys. 83 1140
[3] Suzuki Y 1991 Nucl. Phys. A 528 395
[4] Ikeda K 1992 Nucl. Phys. A 538 355
[5] Funada S, Kameyama H and Sakuragi Y 1994 Nucl. Phys. A 575 93
[6] Aoyama S, Mukai S, Katō K and Ikeda K 1995 Prog. Theor. Phys 93 99
[7] Kobayasi T 1992 Nucl. Phys. A 538 343
[8] Simon H et al. 1999 Phys. Rev. Lett. 83 496
[9] Katō K, Yamada T and Ikeda K 1999 Prog. Theor. Phys. 101 119
[10] Myo T, Katō K, Toki H and Ikeda K, 2007 Phys. Rev. C76 024305
[11] Myo T, Katō K, Aoyama S and Ikeda K 2001 Phys. Rev. C63 054313