

Deuteron-like correlation of valence nucleons for the $T = 0$ channel in ^{18}F

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Abstract. We study the deuteron-like correlation of the valence proton and neutron with the $T = 0$ channel in ^{18}F using an efficient calculational formalism; the cluster-orbital shell model approach. In this study, we show a particular configuration $[j_1 \otimes j_2]_T^J = [d_{5/2} \otimes d_{3/2}]_0^1$ is the key ingredient for the $T = 0$ pair formation. Also, the continuum contributions plays an important role of the spatial correlation of the proton and neutron.

1 Introduction

Deuteron is the lightest bound system. In the case for the proton and neutron in a nucleus, the spin-orbit interaction from the core nucleus separates the single-particle orbits of j_{\geq} , and the coupling scheme is changed from the free deuteron. It has been pointed out that the $[j_1 \otimes j_2]_T^J = [j_> \otimes j_<]_0^1$ configuration in the same major shell plays an important role for the $T = 0$ channel correlation [1–3]. In our study, sharing the basic aim with the previous works, we investigate how the coupling of the spin-orbit partners, $[j_> \otimes j_<]_0^1$ affects to the $T = 0$ channel correlation in ^{18}F . We also examine how the valence proton and neutron in ^{18}F are spatially localized with the presence of the $[j_> \otimes j_<]_0^1$ channel coupling and continuum states with higher partial-wave.

For the purpose of precise investigation to the valence nucleons including unbound states, an appropriate theoretical approach, which is capable to treat the unbound states within the same footing as the bound states, is needed. Because, for the nucleons above the ^{16}O core, only two orbits, $0d_{5/2}$ and $1s_{1/2}$ are bound, and all other states are unbound states. Therefore, we employ the cluster-orbital shell model (COSM) approach [4]. By using the $^{16}\text{O}+N$ potential which reproduces the bound and unbound states of ^{17}O and ^{17}F [5], we show how the $[j_> \otimes j_<]_0^1$ configuration and the continuum states enhance the correlation energy of the $T = 0$ channel and also discuss the deuteron-like spatial localization arisen due to the continuum contribution.

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2 Model and formalism

We employ the cluster-orbital shell model (COSM) approach [4] to study ^{18}F in an $^{16}\text{O}+p+n$ three-body model. The Hamiltonian of COSM is formulated as follows:

$$\hat{H} = \sum_{i=1}^2 (\hat{t}_i + \hat{v}_i^{\text{CN}}) + (\hat{T}_{12} + \hat{V}_{12}), \quad (1)$$

where $\hat{T}_{12} = \mathbf{p}_1 \cdot \mathbf{p}_2 / M_C$ is the recoil term coming from the subtraction of the center of mass motion due to the finite mass M_C of the core nucleus. The basis set of COSM is constructed in the jj -coupling scheme using basis functions ϕ_α defined in the coordinates of the core+ N subsystems as

$$\Phi_m \equiv \mathcal{A} \left\{ [\phi_{\alpha_1} \otimes \phi_{\alpha_2}]_{T M_T}^{J M} \right\}_m = \mathcal{A} \left\{ u_1(r_1) u_2(r_2) \cdot [j_1 \otimes j_2]_{J M} \cdot [\chi_1^\tau \otimes \chi_2^\tau]_{T M_T} \right\}_m, \quad (2)$$

where α_i denotes a set of the angular momentum and the isospin of the i th particle. The eigenstates of the Hamiltonian, $\hat{H}\Psi_k = E_k\Psi_k$ are described by the expansion using Φ_m as, $\Psi_k = \sum_m C_m^{(k)} \Phi_m$. For the radial part of the basis function, we apply the Gaussian expansion method [6],

$$\phi_{\alpha_i}(r_i) = N_i r_i^{\ell_i} \exp\left(-\frac{1}{2} a_i r_i^2\right) |j_i m_i\rangle |\chi_i^\tau\rangle, \quad (3)$$

where a_i is determined in a variational procedure, and N_i is the normalization.

For the $^{16}\text{O}+N$ potential, we use the same interaction applied in Refs. [5, 7]. This potential reproduces the energy of lowest three states; $5/2^+$, $1/2^+$ and $3/2^+$ of ^{17}O and ^{17}F . For the two-body interaction part \hat{V}_{12} , we use an effective nucleon-nucleon interaction, *i.e.* the Minnesota potential [8]. We introduce an isospin dependence to \hat{V}_{12} by multiplying a factor as 0.85 ($T = 0$) and 1.50 ($T = 1$) in order to adjust to the experimental binding and excited energies of ^{18}F .

3 Results and discussions

3.1 Physical quantities of ^{18}F

One of the way to examine the property of the ground (1^+) and first excited (0^+) states is to calculate the $M1$ transition strength $B(M1; 0^+ \rightarrow 1^+)$. Our calculation gives the large $B(M1)$ -value as $18.40 \mu_N^2$, which almost corresponds to the experimental one, $19.71 \mu_N^2$ [9]. Other theoretical approaches give 15.18 [10] and $18.15 (\mu_N^2)$ [3]. Here, the essential difference between Ref. [10] and [3] is the inclusion of the $[j_> \otimes j_<]$ component in the model space, and the former one does not include such the component. We consider this component is the key ingredient for the $T = 0$ channel deuteron-like correlation as discussed later and refer to the component as ‘‘cross-term’’ contribution. The magnetic moment of the ground state is not measured in experiments. Our calculation shows the large magnetic moment as $\mu = 0.810 \mu_N$, and the result is consistent with other theoretical calculations, 0.834 [3] and $0.82 (\mu_N)$ [11]. Since the magnetic moment is sensitive to the spin-coupling scheme of the wave function, we decompose to the orbital angular momentum and spin parts; μ^L and μ^S as follows:

$$\mu = \left\langle \sum_i g_l^{(i)} \mathbf{l}_i \right\rangle + \left\langle \sum_i g_s^{(i)} \mathbf{s}_i \right\rangle \equiv \mu^L + \mu^S. \quad (4)$$

If the ^{18}F ground state has a $S = 1$ channel dominance, μ^S becomes large. Our calculation follows such the situation, *i.e.* $\mu^L = 0.091$ and $\mu^S = 0.719 (\mu_N)$. Hence, in the 1^+ state of ^{18}F , the orbital angular momentum part is small, and the $S = 1$ channel is dominant.

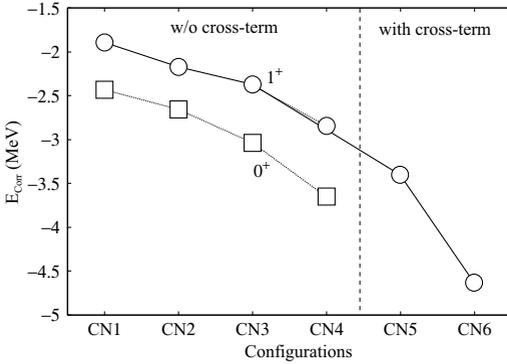


Figure 1. Configuration dependence of the correlation energies for the 1^+ ($T = 0$) and 0^+ ($T = 1$) state of ^{18}F . Open circles and squares correspond to the calculations for the 1^+ and 0^+ states, respectively. For the definition of the numbers of the configurations “CN#”, please see text. The lines are to guide the eye.

3.2 Configuration dependence and deuteron-like correlation

In the previous section, we showed that the valence proton and neutron are correlated with the $S = 1$ channel dominance in the ground state of ^{18}F ($T = 0$). Next, we discuss the importance of two ingredients for the deuteron-like correlation; the cross-term and the continuum contributions. To this end, we classify the set of basis functions into six types of configurations labeled as “CN#” and see the configuration dependence. For the series with the $(\ell_j)^2$ -type coupling of the angular momentum part, we use CN1, CN2, CN3 and CN4, which are set of basis functions with $(d_{5/2})^2$, $(s_{1/2})^2$, $(d_{3/2})^2$ and $(pf)^2$. Here, for example, CN2 includes $(s_{1/2})^2$ in addition to CN1; $(d_{5/2})^2$, and other configurations, CN3 and CN4 are defined as the same manner. CN5 includes the “cross-term” $(d_{5/2})(d_{3/2})$ and $(s_{1/2})(d_{3/2})$ in addition to CN3, and CN6 is the full configuration up to pf -waves including the cross-term.

The configuration dependence of the correlation energies and magnetic moments are shown in Figs. 1 and 2. The correlation energy is defined as $E_{\text{Corr}}^{n\ell_j}(J^\pi) \equiv E(J^\pi) - (\epsilon_{0d_{5/2}}^\pi + \epsilon_{0d_{5/2}}^\nu)$, where $E(J^\pi)$ is the three-body energy. First, we focus on the results with the series of the $(\ell_j)^2$ -type configurations (CN1, CN2, CN3 and CN4). The absolute values of the correlation energies for both 1^+ and 0^+ almost monotonically become large with increasing the number of the configurations, and the results of the 1^+ and 0^+ are similar each other. Moreover, for the $(\ell_j)^2$ -type configurations, the change of the magnetic moment of the 1^+ state is small, and the orbital part μ^L is systematically larger than the spin part μ^S .

Next, we discuss the importance of the “cross-term” contribution in the 1^+ state (CN5) to gain the correlation energy and to change the coupling scheme of the valence nucleons. With the CN5 configuration, the correlation energy of the 1^+ state drastically increases as $E_{\text{Corr}} = -3.41$ MeV and is even larger than that of CN4 (-2.85 MeV), which includes the $(pf)^2$ configurations to the model space. From CN3 to CN5, the magnetic moment increases from 0.613 to 0.779 (μ_N). The role of the angular momentum part μ^L and spin part μ^S are interchanged drastically. μ^S increases from 0.262 to 0.646 (μ_N), and μ^L decreases from 0.351 to 0.133 (μ_N). The large contribution of the spin-part μ^S at CN5 is an evidence of the importance of the cross-term to change the coupling scheme of the wave function from the jj -coupling to LS -coupling with $S = 1$.

The other important ingredient is the continuum contribution. Since all of the pf -waves with this potential model are obtained as the unbound states, the calculations with CN4 and CN6 correspond to the inclusion of the continuum contributions. With the CN6 configuration, the correlation energy is obtained as -4.64 MeV. The calculated value shows the continuum contribution is equally important to the cross-term one. However, the effect of the continuum contribution depends on the presence of the cross-term. This is because that without the cross-term (CN4), the correlation energy becomes less than half of the CN6 case.

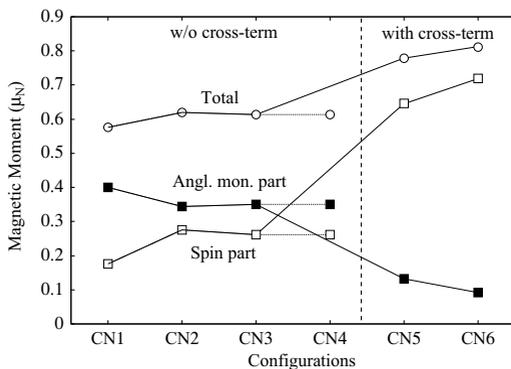


Figure 2. Configuration dependence of magnetic moment for $^{18}\text{F}(1^+)$. For the definition of the numbers of the configurations “CN#”, please see text.

4 Summary and discussion

We study the deuteron-like correlation of the valence neutron and proton in ^{18}F using the COSM approach. From the analysis, we showed the essential ingredients of the deuteron-like correlation are the cross-term, which is the coupling of the spin-orbit partners j_{\pm} , and the continuum contributions. In the model space of the $(\ell_j)^2$ -type configurations, the property of the correlation energies of the $T = 1$ and $T = 0$ channels becomes similar with the change of the number of basis functions. The cross-term component, $[d_{5/2} \otimes d_{3/2}]$ in ^{18}F changes the correlation energy drastically. The magnetic moment also increases, and its spin part becomes dominant by including the cross-term. The continuum contribution is the other important ingredient for the deuteron-like spatial correlation. The calculated opening angle of valence nucleons show the spatially localized deuteron-like correlation of the proton and neutron in ^{18}F .

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