High-momentum components in the $^4$He nucleus caused by inter-nucleon correlations

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Abstract

High-momentum components of nuclei are essential for understanding the underlying inter-nucleon correlations in nuclei. We perform the comprehensive analysis for the origin of the high-momentum components of $^4$He in the framework of Tensor-optimized High-momentum Antisymmetrized Molecular Dynamics (TO-HMAMD), which is a completely variational approach as an ab initio theory starting from the bare nucleon-nucleon interaction. The analytical derivations are provided for the nucleon momentum distribution of the Antisymmetrized Momentum Dynamics (AMD) wave functions, with subtraction of center-of-mass motion. The nucleon momentum distribution for $^4$He is calculated by applying a new expansion technique to our ab initio wave function, and agrees with the experimental data up to the high-momentum region. Fine-grained analysis is performed for the high-momentum components in $^4$He with respect to different nucleon correlations. Contributions from tensor, central with short-range, and many-body correlations are extracted from the nucleon momentum distributions. The manifestation of tensor correlation around 2 fm$^{-1}$ region is explicitly confirmed by comparing the momentum distributions predicted using different types of $NN$ interactions with and without the tensor force.

Keywords: high-momentum component; momentum distribution; inter-nucleon correlation; tensor force; short-range repulsion (correlation)

1. Introduction

In atomic nuclei, the high-momentum components provide an important window for understanding the underlying inter-nucleon correlations induced by the bare nucleon-nucleon ($NN$) interactions [1]. The high-momentum components are known to contribute about 20% to the total wave function in both finite nuclei [2, 3, 4] and nuclear matter [6, 5]. In the reproduction of the high-momentum components, it is essential to describe correctly the strong $NN$-correlations in the nuclear wave function, which is the major difficulty of the ab initio calculations for nuclear systems. For the $NN$ correlations, it is well known that both tensor and short-range correlations are induced by the attraction from tensor force and the short-range repulsion respectively, in the bare interaction [7]. Accordingly, many-body wave functions are built upon the $NN$-correlation functions. In the Green’s Function Monte Carlo (GFMC) method [7], a Jastrow type of correlation function is introduced in the trial wave function, and is assumed to be a product form of many-kinds of $NN$-correlation functions. In Ref. [8], the unitary operators are introduced for the inter-nucleon correlations of tensor and short-range types.

Recently, the “Tensor-optimized Antisymmetrized Molecular Dynamics” (TOAMD) method is developed in Refs. [9, 10, 11, 12, 13] by multiplying the $NN$-correlations into the “Antisymmetrized Molecular Dynamics” (AMD) reference wave function, which itself is a microscopic framework successfully applied in the study of nuclear cluster states [14, 15]. Both the tensor correlation function $F_D$ and the central correlation function $F_S$ are introduced in the TOAMD wave function. By including up to the second orders in the cluster expansion, $i.e. F_{D,S}$ and $F_{D,S}^2$, the TOAMD wave function reproduces well the binding energies and radii of s-shell nuclei using the AV8$'$ bare interaction [10]. In later works, it is also found that the tensor [16] and short-range [17] correlations are well described using the high-momentum $NN$ pairing technique [18], which is named as the “High-momentum Antisymmetrized Molecular Dynamics” (HM-AMD) in Refs. [16, 17]. This technique has been applied to the calculations of both finite nuclei [16, 17, 18, 20, 19] and nuclear matters [21, 22]. Hybridizing the TOAMD and HM-AMD methods, the “Tensor-optimized High-momentum Antisymmetrized Molecular Dynamics” (TO-HMAMD) approach is formulated, which also provides the same quality of the nuclear properties of $^2$H [23] and $^4$He [24] as other ab initio calculations in TOAMD or GFMC frameworks. In the methods of TOAMD, HM-AMD, and TO-HMAMD, the wave functions are variationally determined by minimiz-
ing the total energies, and the high-momentum components are produced naturally in the optimized wave function. In the TOAMD wave function, the NN correlations are described by using the variational correlation functions. The tensor correlation $F_D$ is inherited from the preceding “Tensor-optimized Shell Models” (TOSM) approach which provides good descriptions for the light nuclei [25, 26, 27, 28, 29]. In Ref. [29], it is found that the spatial shrinkage of particle states is essential for the tensor contribution, which is further discussed in Ref. [18] and related to the emergence of high-momentum components in nuclei.

Experimentally, the high-momentum components are probed by using the electron scattering [30, 2, 3, 4, 31, 32] and the proton induced reactions [33]. Nucleon momentum distributions of light nuclei are provided in Ref. [30]. In Ref. [2], the tensor correlation is suggested by the prominent population of the proton-neutron pairs in the high-momentum region. More recent developments are introduced in review papers [3, 4].

Theoretically, the momentum distributions of light nuclei have been calculated using bare interactions [34, 35, 36, 37, 38, 39, 41, 40]. For $^4$He nucleus, the origin of the high-momentum components has been discussed in various studies. In Ref. [34], the momentum distribution is calculated using Reid NN force and the contributions from S- and D-wave components are discussed, while the binding energy of $^4$He is not reproduced in this reference. In Ref. [38], the proton momentum distributions are compared for the central and central+tensor channels of the Variational Monte Carlo wave function. In Ref. [40], the spin-isospin decomposition is performed for the proton momentum distribution. However, the inter-nucleon correlations become complex in many-body system and then the physical origins of high-momentum components has not been clarified in relation to the inter-nucleon correlations, such as the tensor or short-range ones. For example, the nucleon momentum distribution excited by the short-range repulsion can be coupled to the uncorrelated term in the reference 0-state in $^4$He. In addition, the contributions from many-body correlations beyond the two-body case, which correspond to the second or higher orders of cluster expansion, is unknown. Hence, it is worthwhile to perform the thorough investigations on the origins of the high-momentum components with respect to different types of inter-nucleon correlations. In the present work, we provide a general method to calculate the momentum distribution of nuclei with our $ab~initio$ approach of TO-HMAMD [24]. Using this method, we perform the fine-grained analysis for the physical origins of high-momentum components in the $^4$He nucleus. We also investigate the importance of the tensor correlation in the high-momentum region by comparing the results using different NN interactions with and without the tensor force.

2. Formulation

We describe the nucleon momentum distribution of the $^4$He nucleus in the framework of TO-HMAMD. In Sec. 2.1 we introduce the formulation of TO-HMAMD wave function. In Sec. 2.2, we provide the first formulation for the nucleon momentum distribution of the (HM-)AMD wave functions. In Sec. 2.3, we introduce a projection approach to expand the $ab~initio$ TO-HMAMD wave function by using the HM-AMD bases, for the calculation of momentum distributions.

2.1. The $ab~initio$ wave function of $^4$He

We recapitulate the theoretical framework for the $ab~initio$ wave function used in this work. Detailed explanations are found in Ref. [24] and references there in.

In the coordinate space, the (HM-)AMD wave function with mass number $A$ is written as

$$|\Psi_{(HM)AMD}\rangle = A \left\{ \prod_{i=1}^{A} \psi_\alpha(r_i, Z_i) \right\},$$

where $A$ is the antisymmetrizer and the nucleon state $\psi_\alpha$ is given as the Gaussian wave packet

$$\psi_\alpha(r, Z) \propto e^{-\nu(r-Z)^2} \chi_\alpha.$$  

Here $\alpha$ denotes the spin and isospin of the nucleon state and the range parameter $\nu$ is determined in the energy variation. Coordinate $Z$ is the centroid of Gaussian wave packets which is typically real satisfying the condition of $\sum_i Z_i = 0$. For HM-AMD wave functions, the imaginary shifts $\pm iD$ are additionally introduced in a pairwise form for two nucleons among $A$-nucleons as

$$Z_i \rightarrow Z_i + iD,$$

$$Z_j \rightarrow Z_j - iD,$$

where the imaginary shift $D$ represents the momentum component of the Gaussian wave packet in Eq. (2) such as $\langle k \rangle = 2\nu D$. From this property, using a large magnitude of $D$, we can describe the high-momentum components induced by the NN correlations. While Eq. (3) describes only single NN pair using $iD$, another pair with different $iD'$ can be successively added in a HM-AMD basis to describe simultaneously the correlations induced by two NN pairs [17, 24]. The wave functions that include HM-AMD bases of up to single or double NN pairs are named as “Single HMAMD” and “Double HMAMD”, respectively. The TO-HMAMD wave function is then formulated using correlation functions $F_D$ and $F_S$ as

$$|\Psi_{TO-HMAMD}\rangle = (1 + F_D + F_S) |\Psi_{HM-AMD}\rangle,$$

where

$$F_D = \sum_{i<j}^{A} \sum_{t} f_D^t(r_{ij}) O_{ij}^t r_{ij}^2 S_{12}(r_{ij}),$$

$$F_S = \sum_{i<j}^{A} \sum_{t,s} f_S^t(s_{ij}) O_{ij}^t O_{ij}^s.$$

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Here, $F_D$ are the tensor correlation operators and $F_S$ are the central correlation operators, with the operators $O_D^{ij} = (\tau_i \cdot \tau_j)^t$ and $O_S^{ij} = (\sigma_i \cdot \sigma_j)^t$. Superscripts $s$ and $t$ are used to distinguish the spin and isospin channels. The pair functions $f_D^s$ and $f_S^{sl}$ are determined in the minimization of the total energy. When imaginary shifts $\iota D$ are not included in Eq. (4), the wave function reduces to the TOAMD wave function of the first order [9]

$$|\Psi_{\text{TOAMD}}\rangle = (1 + F_D + F_S) |\Psi_{\text{AMD}}\rangle .$$ (7)

Using the TO-HMAMD wave function in Eq. (4), we obtain the total energy as $-24.74$ MeV and the radius as 1.51 fm for the $^4$He nucleus with AV8$'$ bare interaction [24], which reproduce the GFMC results. From these results, we expect that the high-momentum components are accurately described by the TO-HMAMD wave function as an ab initio approach.

### 2.2. Momentum distribution for (HM-)AMD wave function

The (HM-)AMD wave function in the momentum space $\Phi$ can be written as

$$\Phi^{(\text{HM-})\text{AMD}}(k_1, \ldots, k_A) = A \left\{ \prod_{i=1}^A \phi_{\alpha_i}(k_i, Z_i) \right\}$$ (8)

where $k_i$ denotes a momentum of each nucleon in the laboratory frame, and $\phi_{\alpha}(k, Z)$ is the Fourier transformation of the nucleon wave function $\psi_{\alpha}(r, Z)$ in Eq. (2). The (HM-)AMD wave function has a spurious center-of-momentum component $\Phi_G(k_G)$ which can be factorized in Eq. (8) as

$$\Phi = \Phi_1 \cdot \Phi_G(k_G) ,$$ (9)

where $\Phi_1$ is the internal wave function and the center-of-mass momentum is given as $k_G = \sum_{i=1} A k_i$ and

$$\Phi_G(k_G) = \frac{1}{(2\pi \nu \epsilon)^3/4} e^{-k_G^2/(4\nu \epsilon)} .$$ (10)

The operator of the nucleon momentum distribution is defined as

$$\hat{n}(k) \equiv \sum_{i=1}^A \delta (b_i - k) ,$$ (11)

where $b_i$ is a nucleon momentum in the center-of-mass frame satisfying $k_i = b_i + k_G/A$ and $\sum_{i=1} k_i = 0$. Similarly, we define the nucleon momentum distribution operator in the laboratory frame as

$$\hat{n}_G(k) \equiv \sum_{i=1}^A \delta (k_i - k) .$$ (12)

The expectation value of $\hat{n}_G(k)$ can be calculated directly using the (HM-)AMD wave function as

$$n_G(k) = \frac{\langle \Phi | \hat{n}_G | \Phi \rangle}{\langle \Phi | \Phi \rangle} = \frac{1}{(2\pi)^3} \int dr e^{-ik \cdot r} \cdot \tilde{n}_G(r) ,$$ (13)

where

$$\tilde{n}_G(r) = \sum_{i=1}^A \frac{\langle \Phi | e^{ik \cdot r} | \Phi \rangle}{\langle \Phi | \Phi \rangle} = \sum_{i,j=1}^A \langle \phi_i | e^{ik \cdot r} | \phi_j \rangle \cdot B_{ji}^{-1} .$$ (14)

We note that in Eq. (14) the integrations are performed in momentum space over momentum $k$, and $B_{ij} = \langle \phi_i | \phi_j \rangle$ is the overlap matrix of single nucleon states where we simply write it without $\alpha$. On the other hand, the expectation value of $\tilde{n}_G(k)$ can be given using $b_i$ and the relation in Eq. (9) as

$$\tilde{n}_G(r) = \sum_{i=1}^A \frac{\langle \Phi | e^{ib_i \cdot r} | \Phi \rangle}{\langle \Phi | \Phi \rangle} = \frac{1}{(2\pi)^3} \int d r e^{-i k \cdot r} \cdot \tilde{n}_G(r) \cdot \exp \left[ -\frac{\nu r^2}{2A} \right] .$$ (15)

The nucleon momentum distribution in the center-of-mass frame can now be expressed using Eq. (15) as

$$n(k) = \frac{\langle \Phi_1 | \tilde{n} | \Phi_1 \rangle}{\langle \Phi_1 | \Phi_1 \rangle} = \frac{1}{(2\pi)^3} \int d r e^{-i k \cdot r} \cdot \tilde{n}_G(r) \cdot \exp \left[ -\frac{\nu r^2}{2A} \right] .$$ (17)

Substituting Eq. (12) into Eq. (17) we have the momentum distribution in (HM-)AMD

$$n(k) = \frac{1}{(2\pi \nu \epsilon)^3/2} \times \sum_{i,j=1}^A \exp \left[ -\frac{1}{2 \nu \epsilon} (k - iv(Z_i^* - Z_j))^2 \right] B_{ij} B_{ji}^{-1} ,$$ (18)

where $\epsilon = (A - 1)/A$. We note that for HM-AMD wave functions, the centroid parameters $Z_{i,j}$ in Eq. (18) are complex with imaginary shifts. The momentum distribution satisfies the normalization condition

$$\int d k \ n(k) = A .$$ (19)

We note that the equations above are formulated in general for nucleus with any mass number $A$. In addition, the center-of-mass motion is completely subtracted in this formulation, which is an significant advantage of this research. When the total wave function $|\Phi\rangle = \sum_{\alpha} c_\alpha |\Phi_\alpha\rangle$ is a superposition of the AMD bases $|\Phi_\alpha\rangle$, the corresponding nucleon momentum distribution is given as

$$n(k) = \frac{1}{\langle \Phi | \Phi \rangle} \sum_{\alpha,b} c_\alpha^* c_b \langle \Phi_\alpha | \tilde{n} | \Phi_b \rangle ,$$ (20)
In (HM-)AMD, usually the angular momentum projection [42] is adopted to restore the rotational symmetry, which is mathematically a superposition of rotated (HM-)AMD bases, and hence the corresponding nucleon momentum distribution of $|\Phi^J_M\rangle$ can be calculated using Eq. (20) for the state with total spin $J$ and $z$-component $M$.

### 2.3. Expansion of TO-HMAMD wave function

To calculate the nucleon momentum distribution of the $ab\ initio$ TO-HMAMD wave function $|\Psi\rangle$, we expand the $|\Psi\rangle$ in coordinate space by a set of HM-AMD bases $\{|\Psi_1\rangle, |\Psi_2\rangle, \ldots, |\Psi_n\rangle\}$ with the number of $n$ as

$$|\Psi\rangle \approx \sum_{i=1}^{n} C_i |\Psi_i\rangle,$$  \hspace{1cm} (21)

where $C_i$ are expansion coefficients. The momentum distribution can be calculated using HM-AMD basis with $ab\ initio$ the state with total spin $J$ and $z$-component $M$. The $ab\ initio$ wave function $|\Psi\rangle$ can be expanded with $|\Psi_k\rangle$ as

$$|\Psi\rangle \approx \sum_k P_k |\tilde{\Psi}_k\rangle,$$  \hspace{1cm} (23)

where

$$P_k = \langle \tilde{\Psi}_k | \Psi \rangle.$$

Using Eqs. (22) and (23), the coefficients $C_i$ are obtained as

$$C_i = \sum_k \tilde{\psi}_{i,k} P_k$$  \hspace{1cm} (25)

In realistic calculations, the number $n$ of the HM-AMD bases used in Eq. (21) is finite and the quality of this expansion can be estimated using the overlap

$$O = \langle \Psi | \sum_k P_k |\tilde{\Psi}_k\rangle = \sum_k P_k^2.$$  \hspace{1cm} (26)

For accurate expansion, the overlap $O$ should be close to unity.

### 3. Results

We first check the overlap $O$ by successively enlarging the functional space expanded by the HM-AMD bases, as shown in Table 1 and Fig. 1. The setups of the Single HMAMD bases are the same as in Ref. [24], and the Double HMAMD bases are additionally included. The overlap value $O = 99.8\%$ is obtained for the TOAMD wave function, which confirms the accuracy and reliability of this expansion method [24]. It is found that when the Single HMAMD bases are included, the overlap $O$ for the TO-HMAMD wave function is $O = 97.5\%$, almost unity. This is surprising because it is known that the second order of the NN correlations is important to converge the solutions of the $ab\ initio$ wave functions of nuclei [10] and they are expected to be described using Double HMAMD bases [24]. To understand this behavior, we note that the Single HMAMD bases are not orthogonal to the Double HMAMD bases, hence the effects of the second order terms are partially included in the expansion within the Single HMAMD functional space. In this work, we perform the expansion within Single HMAMD bases so as to get the sufficient numerical accuracy for the momentum distribution of nuclei.

| n     | $+D_z$ | $+D_{\nu}$ | $+D_{\nu}D'$ |
|-------|-------|-----------|-----------|
| $O$(TOAMD) | 0.888 | 0.960    | 0.998    |
| $O$(TO-HMAMD) | 0.771 | 0.912    | 0.975    | 0.982 |

Table 1: Overlap $O$ between the $ab\ initio$ wave function and its expansion with respect to the successive additions of HM-AMD bases. “$+D_z$” and “$+D_{\nu}$” denote the additions of Single HM-AMD bases with imaginary shifts in $z$- and $x$-directions, respectively. “$+D_{\nu}D'$” denotes the addition of Double HMAMD bases. The total number of HM-AMD bases used for expansion is $n$.

![Figure 1: Overlap $O$ between the $ab\ initio$ wave function and its expansion with respect to the successive additions of HM-AMD bases. Notations are the same as used in Table 1.](image)

Before showing the final results, we demonstrate the momentum distributions of the $^4$He nucleus described by the HM-AMD wave functions in the intrinsic frame. For the (HM-)AMD bases, Re($Z$) = 0 is commonly adopted for all nucleons. For the AMD basis with $D = 0$, the spherical Gaussian distribution in the momentum space is obtained in Fig. 2 (a). The effect of paired imaginary shifts $D_{\nu}=\pm 5$ fm in a HM-AMD basis of $^4$He is shown in Fig. 2 (b), where additional two peaks of momentum distribution is observed at corresponding $k_z=2\nu D_{\nu}=\pm 2.0$ fm$^{-1}$. Fig. 2 (c) and (d) show the intrinsic nucleon momentum distributions after superposing successively the (HM-)AMD bases with various kinds of imaginary shifts.
in z- and x-directions, where the high-momentum components beyond 2 fm$^{-1}$ are clearly shown as compared to the AMD basis in Fig. 2 (a).

![Figure 2: Momentum distributions of $^4$He nucleus described by the (HM-)AMD wave functions in the intrinsic frame. Panel (a) is the nucleon momentum distribution of the AMD basis without imaginary shifts ($D = 0$). Panel (b) is the one for the HM-AMD basis with paired imaginary shifts $D_x = \pm 5$ fm. Panel (c) is the nucleon momentum distribution of the superposed (HM-)AMD bases with various z-direction imaginary shifts $D_z$. Last Panel (d) is the nucleon momentum distribution of superposed (HM-)AMD bases with imaginary shifts in both x- and z-directions. Unit of the distribution is in fm$^{3}$.

We calculate the nucleon momentum distribution for the $^4$He nucleus using both the TOAMD and the TO-HMAMD wave functions, and the results are compared to experimental values in Fig. 3. It is found that both the TOAMD and the TO-HMAMD wave functions nicely describe the high-momentum components, as shown by the solid curve and the dashed curve, respectively. In particular, the TO-HMAMD wave function contains more components of higher momentum and reproduces better the experimental data with enhanced high-momentum tail, especially the inclusive data denoted by open squares, as compared to the dashed curve.

![Figure 3: Nucleon momentum distribution of the $^4$He nucleus calculated using two-kinds of the wave functions of TO-HMAMD and TOAMD. The AV8$^\ast$ bare interaction is used to obtain the wave function. The dash-dotted curve and the experimental data are adopted from Ref. [30]. “VMC” denotes the distribution calculated with the Variational Monte Carlo wave function [35]. The open squares represent the values extracted from inclusive $^4$He(e,$e'p$)X reaction data. The full and open triangles represent the values extracted from the exclusive $^4$He(e,$e'p$)X reaction data. The nucleon momentum distribution is normalized as $\int_0^{\infty} dk k^2 n(k) = 1$.

Here $|\Psi_0\rangle$ is the AMD wave function which corresponds to the uncorrelated state, $|\Psi_1\rangle$ and $|\Psi_2\rangle$ are the two-body N-N-correlated terms in the central and tensor channels, respectively. $F_S$ and $F_D$ are the two-body correlation operators adopted from the TOAMD wave function in Eq. (7) for the first order of cluster expansion, and the central term $|\Psi_S\rangle$ contains the short-range correlation at the two-body level. $|\Psi_S\rangle$ is the term of many-body correlations which are not included in the TOAMD wave function. Coefficients $n_0, ..., n_3$ are normalization factors. Then, the ab initio wave function $|\Psi\rangle$ can be expanded as

$$|\Psi\rangle = C_0 |\Psi_0\rangle + C_1 |\Psi_1\rangle + C_2 |\Psi_2\rangle + C_3 |\Psi_3\rangle ,$$

where the coefficients $C_i = \langle \Psi |\Psi_i\rangle$ and the probabilities of each term are given as $|C_i|^2$, as shown in Fig. 4. In this calculation, we found that the correlated terms contribute to about 23% of the total wave function in total, which is consistent with the general estimation of 20% [4]. The contribution of tensor correlation term $|\Psi_2\rangle$ is about 12%, which is slightly smaller than the 13% for D-wave components in Ref. [12]. This is reasonable because the many-body term $|\Psi_3\rangle$ also contains small amount of D-wave components. It is interesting to note that contribution from tensor correlation is almost double as compared to the central contribution. The many-body contribution of about 4% is comparably small, although this term contributes to about 10 MeV in the binding energy of $^4$He [10].

Using the wave function in Eq. (28), we calculate the nucleon momentum distribution for each component using the expansion method introduced in Sec. 2.3, and the re-
results are shown in Fig. 5. In this figure, contributions from the AMD, central, tensor, and many-body terms are clearly decomposed from the total momentum distribution of the $^4$He nucleus. It is found that the high-momentum components ($k > 2$ fm$^{-1}$) of $^4$He nucleus are mostly contributed by the tensor and the short-range correlated terms, where the tensor correlation dominates around $k \approx 2$ fm$^{-1}$ and the short-range correlation dominates around $k \approx 4$ fm$^{-1}$, as denoted by the blue and yellow regions in the figure, respectively. The contribution from many-body correlation term is found to be comparably small for $k < 4$ fm$^{-1}$ in this calculation.

Using the characteristics of tensor dominance around $k \approx 2$ fm$^{-1}$, the tensor correlations in $^4$He can be confirmed by the shape of nucleon momentum distribution, as shown in Fig. 6. In this figure, we compare two sets of momentum distributions predicted by using the AV4' and the AV8' interactions, with experimental values. Both the AV4' and the AV8' interactions are renormalized from the realistic AV18 interaction to reproduce the binding energies of light nuclei [1] and both interactions include strong short-range repulsion in the central channel while AV4' does not have the tensor and LS force. In dashed curve with AV4', no tensor correlations are included in the wave function. Hence, we observe a deep valley structure around $k \approx 2$ fm$^{-1}$, which deviates significantly from the experimental data. On the other hand, in the wave function using the AV8' interaction, the tensor correlations are induced by the $NN$ tensor force. Consequently, a smooth solid curve is obtained and nicely reproduces experimental data. This comparison provides a clear signature for the validation of the tensor correlation in $^4$He nucleus.

4. Conclusion

We provided the fine-grained analysis for the different types of inter-nucleon correlations in the $^4$He nucleus and investigated their contributions to the high-momentum components. The nucleon momentum distribution of the $^4$He nucleus was calculated by using the ab initio wave function in the TO-HMAMD framework with the AV8' interaction. The first analytical formulation was derived for the nucleon momentum distribution of (HM-)AMD wave functions, with complete subtraction of the center-of-mass motion. In this work, the TO-HMAMD wave function was expanded by using the HM-AMD bases using a new projection method, and it was found that a good precision is obtained for the expansion. Based on these theoretical preparations, we calculated the nucleon momentum distributions for the TOAMD and the TO-HMAMD wave functions. It was found that both calculations predict the high-momentum components and the distribution calculated from the TO-HMAMD wave function reproduces the

Figure 4: Probabilities of each orthogonal component of AMD, central, tensor, and many-body in the TO-HMAMD wave function of $^4$He.

Figure 5: Decomposition of the high momentum component of the $^4$He nucleus. “Total” denotes the nucleon momentum distribution of the entire TO-HMAMD wave function. “AMD”, “Central”, and “Tensor” denote nucleon momentum distributions contributed by corresponding component defined in Eq. (27).

Figure 6: Nucleon momentum distribution of $^4$He calculated with the AV4' and the AV8' interactions in the TO-HMAMD framework. The experimental data and normalization are the same as in Fig. 3.
experimental data with a clear difference to the TOAMD case, which shows the the effect of many-body correlation. The physical origins of the high-momentum component were further clarified via the decomposition of the total wave function into the orthogonal components consisting of AMD, central, tensor and many-body channels, and their contributions to the momentum distribution were calculated individually. The tensor dominance around \( k \approx 2 \) fm\(^{-1}\) and the short-range dominance around \( k \approx 4 \) fm\(^{-1}\) were observed from the decomposition. The relatively small contribution from the many-body correlation was also obtained. At last, the nucleon momentum distributions calculated by using both the AV4′ and the AV8′ interactions were compared with the experimental data, and the tensor correlation was found to be essential to reproduce the smooth momentum distribution around \( k \approx 2 \) fm\(^{-1}\) in the experimental data, which provides a clear manifestation for the existence of tensor correlation in the \(^4\)He nucleus. This work completes the previous understanding of high-momentum component in the \(^4\)He nucleus, and is expected to be useful for the theoretical and experimental studies in future for other heavier nuclei.

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