Properties of the tensor correlation in He isotopes

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Abstract. We investigate the roles of the tensor correlation on the structures of $^4$\textsuperscript{5}He. For $^4$He, we take the high angular momentum states as much as possible with the $2p2h$ excitations of the shell model type method to describe the tensor correlation. Three specific configurations are found to be favored for the tensor correlation. This correlation is also important to describe the scattering phenomena of the $^4$He+$n$ system including the higher partial waves consistently.

1. Introduction

The tensor force is an important ingredient in the nuclear force and plays a characteristic role in the nuclear structure. Actually, we know that the contribution of the tensor force to the binding energy in $^4$He is of the same magnitude as that of the central force[1]. Although there is real space analyses of $^4$He with realistic interaction, it is important to understand the effect of the tensor force on the nuclear structure in a physically transparent manner by describing explicitly the tensor correlation in the model space.

Recently, Sugimoto, Toki and Ikeda have brought a progress in description of the tensor correlation in the model space[2]. Considering the pion as an origin of the tensor force, they showed that the tensor correlation is described as what causes the charge-parity mixing of the single-nucleon orbit mediated by the pion-field. They applied this charge-parity-projected Hartree-Fock method to $^4$He and succeeded in describing the tensor correlation.

The basic purpose of this study is to understand the essential effects of the tensor correlation on the nuclear structure by treating the tensor force explicitly. In this report, we investigate the structure of $^4$He in a shell model type method[3], referring the results of Ref. [2]. We furthermore discuss the effect of the tensor correlation on the $^4$He+$n$ scattering phenomena.

2. Tensor correlation in $^4$He

For $^4$He, we extend the shell model type wave function from the conventional $(0s)^4$ configuration into the configuration mixing of $(0s)^4+(0s)^2(0p)^2+\cdots$ within the $2p2h$ excitations to describe the tensor correlation, that is, the $2p2h$ configurations can be coupled with the $(0s)^4$ one by the tensor force. We, furthermore, express the radial part of the particle states by superposition of the Gaussian basis functions beyond the harmonic oscillator ones. This is important to describe the spatial shrinkage of the particle orbits caused by the tensor force[2, 3, 4]. The hole state ($0s$ orbit) has a simple harmonic oscillator basis with length parameter $b_{0s}$.
Table 1. Properties of the obtained $^4$He ground state.

| Property                   | Value       |
|----------------------------|-------------|
| Energy                     | $-28.0$ MeV |
| $\langle V_{\text{tensor}} \rangle$ | $-51.0$ MeV |
| Matter radius               | $1.48$ fm   |
| D-state probability         | $9.6\%$    |

$(0s_{1/2})^4$ $10(0p_{1/2})^0_{10}$ $85.0\%$

$(0s_{1/2})^0_{10}(0p_{1/2})^0_{10}$ $5.0\%$

$(0s_{1/2})^0_{10}(1s_{1/2})^0(0d_{3/2})^0_{10}$ $2.4\%$

$(0s_{1/2})^0_{10}(0p_{3/2})^0(0f_{5/2})^0_{10}$ $2.0\%$

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Figure 1. $^4$He-$n$ scattering phase shifts in comparison with the experiments[6].

We use Akaishi potential constructed from the $G$-matrix theory using the realistic AV8' interaction [4], and adjust the central part in order to fit the experimental matter radius and binding energy of the $^4$He in this model, but retaining the tensor and the LS parts.

We take the orbital angular momentum for particle states up to six ($i$-orbit) and adopt four Gaussian bases with length parameters 0.6, 0.8, 1.0, 1.4 fm for every particle states. These choices are sufficient to achieve the convergences of the solutions, while the momentum components are allowed in the $G$-matrix method. The energy minimum of $^4$He is obtained at $b_0 = 1.37$ fm. The properties of the $^4$He ground states are listed in Table 1, where $\langle V_{\text{tensor}} \rangle$ shows a large contribution. The results mean that our model can describe the tensor correlation. Among the $2p2h$ components, $(0s_{1/2})^2_{JT}(0p_{1/2})^2_{JT}$ with $(J, T) = (1, 0)$ for spin and isospin, is strongly mixed, which represents the pion-like $0^-$ coupling between the $0s_{1/2}$ and $0p_{1/2}$ orbits[2]. Remaining two $2p2h$ components come from the property of the tensor operator $S_{12}$, which changes relative orbital angular momentum and intrinsic spin of two-nucleon system both by two.

3. Tensor correlation in the $^4$He+$n$ scattering

We investigate the tensor correlation for the $^4$He-$n$ scattering phenomena. Since the obtained $^4$He has a large $0p_{1/2}$ component from the tensor correlation, this feature brings the Pauli blocking for the $^5$He$(1/2^-)$ state and the splitting of $1/2^- - 3/2^-$ can arise. To show this, we solve the coupled problem of the "tensor-optimized $^4$He cluster" $+n$ system[3] where we modify a microscopic $^4$He-$n$ interaction, KKNN[5] consisting of central and LS terms. We construct a new $^4$He-$n$ interaction with reducing the LS term by 48% from that of KKNN, shown in Fig. 1. We also investigate the $d$ wave properties in comparison with the KKNN’s (no tensor correlation) results. Our results considering the tensor correlation reproduces the experimental behavior[6], which means that the $^4$He+$n$ scattering is naturally described with the tensor correlation.

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[1] H. Kamada et al., Phys. Rev. C 64(2001)044001.
[2] S. Sugimoto, K. Ikeda, H. Toki, Nucl. Phys. A 740(2004)77.
[3] T. Myo, K. Kato and K. Ikeda, Prog. Theor. Phys. 113(2005)763.
[4] Y. Akaishi, Nucl. Phys. A 738(2004)80.
[5] H. Kanada, T. Kaneko, S. Nagata and M. Nomoto, Prog. Theor. Phys. 61(1979)1327.
[6] Th. Stammbach, and R. L.Walter, Nucl. Phys. A 180(1972)225.