Tensor correlation in neutron halo nuclei

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Abstract. We investigate the effect of the tensor correlation on the light neutron-rich nuclei. We extend the model space of $^4\text{He}$ core with the shell model approach to incorporate the tensor correlation, and $\pi$-like $0^-$ particle-hole correlation is strongly favored. This affects the $LS$ splitting in $^5\text{He}$ and the $0^+_2$ state of $^6\text{He}$. We also investigate that the tensor correlation is suppressed in $^{11}\text{Li}$ for $p^2$ configuration of last two neutrons, which naturally mixes the $s^2$ component in the ground state and produces the halo structure.

1. Introduction

The tensor force is an important ingredient in the nuclear force derived from the meson theory, and plays a characteristic role in the nuclear structure. Actually, we know that the contribution of the tensor force on the binding energy in $^4\text{He}$ is of the same magnitude as that of the central force[1]. Although there is real space analyses of $^4\text{He}$ 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[3]. Considering that the dominant term of the tensor force is expressed by a one-pion exchange potential, they showed that the tensor correlation can be described as what causes the charge-parity mixing of the single-nucleon orbit mediated by the pion-field. They applied this framework of the charge-parity-projected Hartree-Fock method (CPPHF) to $^4\text{He}$ and succeeded in describing the tensor correlation[3].

The basic purpose of this paper is to understand the essential effects of the tensor correlation on the nuclear structure by treating the tensor force explicitly. For this purpose, first $^4\text{He}$ is chosen because of simpleness of its structure. We take a similar framework of the CPPHF, but a simpler and more conventional shell model approach for $^4\text{He}$[4]. We furthermore analyze the light neutron-rich nuclei including halo ones using the extended cluster model with the tensor correlation.

2. Tensor correlation in $^4\text{He}$

For $^4\text{He}$, we extend the shell model type wave function from the conventional $(0s)^4$ configuration into the $(0s)^4+(0s)^2(0p)^2$ configurations under the consideration of the properties of the tensor force, that is, all the $2p-2h$ configurations of $(0s)^2(0p)^2$ can be coupled with the $(0s)^4$ one by the tensor force. We treat the length parameters of two orbits, $b_{0s}$ and $b_{0p}$ (units in fm) as variational ones to conveniently include the higher shell effect caused by the tensor force, because the CPPHF studies of $^4\text{He}$[3, 5] showed the narrower $0p$ orbit than $0s$ orbit.
Figure 1. Results of $^4\text{He}-n$ phase shifts with KKNN-T2 in comparison to experiment[9].

We use Akaishi potential constructed from the $G$-matrix theory using the realistic AV8' interaction [5], and adjust the central part in order to fit the experimental matter radius and binding energy of the $^4\text{He}$ in the present model, but retaining the tensor and the LS parts.

The energy minimum is obtained at $(b_{0p}, b_{0p})=(1.39, 0.79)$, where $\langle V_T \rangle$ has $-29.9$ MeV, showing the largest contribution. These results mean that the tensor force can be incorporated with a small $b_{0p}$ value which describes the higher shell effects. The $2p-2h$ component of $(0s_{1/2})_T^0(0p_{1/2})_T^0$ with $(J,T)=(1,0)$ for spin and isospin, is strongly mixed, about 8% amount the total $2p-2h$ components of 12.5%. This is caused by the strong $0^-$ coupling between the orbits of $0s_{1/2}$ and $0p_{1/2}$ like a pion effect[3].

3. Tensor correlation in $^4\text{He}+n$ scattering

Here, we construct a reliable $^4\text{He}$-interaction with the tensor-correlated $^4\text{He}$ cluster. We start from the KKNN potential[6], a semi-microscopic $^4\text{He}+n$ interaction having central and LS parts constructed with the $(0s)^3$ assumption of $^4\text{He}$. Therefore, there is no tensor correlation of $^4\text{He}$.

In our model, due to the large mixing of $0p_{1/2}$ component from the tensor correlation in $^4\text{He}$, the Pauli blocking mainly occurs in the $^5\text{He}(1/2^-)$ state and the splitting of $1/2^-\rightarrow 3/2^-$ can arise. Similar studies were performed by the old analyses[7, 8]. In fact, we make a new $^4\text{He}+n$ interaction so-called KKNN-T2 with weakening the LS part by 48% by solving the coupled problem of the “tensor-correlated $^4\text{He}$ cluster”-+$n$ model[4]. The results are shown in Fig. 1. We also investigate the $d$ wave phase shifts in comparison to the KKNN’s results. The KKNN-T2 improves the $d$ wave behavior and get closer to the experiments[9], which means that the description of the $^4\text{He}+n$ scattering is naturally improved with considering the tensor correlation.

4. Tensor correlation in $^6\text{He}$ and $^{11}\text{Li}$

We also investigate the structures of $^6\text{He}$ and $^{11}\text{Li}$ with “tensor-correlated core cluster”-+$n+n$ model. Our results show that the tensor suppression occurs in both nuclei when two valence neutrons occupy $0p_{1/2}$ orbit. In $^6\text{He}$, $0^+_2$ state is pushed up about 3 MeV in comparison to the simple three-body model[10]. In the ground state of $^{11}\text{Li}$, we confirm that the $(1s_{1/2})^2$ component increases by about 20%, which naturally produces the halo structure.

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