

The structure change of the ^{28}Si core in $^{32}\text{S}+\alpha$ cluster structure

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Abstract. The $^{28}\text{Si}+\alpha$ cluster structure was studied. We construct the $^{28}\text{Si}+\alpha$ cluster model, where structure change of the ^{28}Si core and the α -cluster breaking are taken into account. It was found that, in the $^{28}\text{Si}+\alpha$ cluster system having α -cluster at the surface of the ^{28}Si core, the structure change of the ^{28}Si core is energetically rather important while the α -cluster breaking is not significant.

1. Introduction

The nuclear clustering plays important roles in ground and excited states of light nuclei. Excited states having core+ α cluster structure called the α -cluster excited state are known to exist in such nuclei as ^{20}Ne [1] and ^{16}O [2], and they are suggested also in ^{40}Ca and ^{44}Ti [3, 4]. Meanwhile, researches of the α -cluster excited state in the middle of sd -shell are still limited, and the existence of α -cluster excited states in this region is an open problem. Recently, $^{28}\text{Si}+\alpha$ excited states of ^{32}S have been suggested in the experiments of α scattering on ^{28}Si and inelastic scattering of ^{32}S [5, 6]. In order to understand structure of the $^{28}\text{Si}+\alpha$ excited states by solving the core- α relative motion, it is important to take into account the structure change of the core nuclei and the breaking of the α -cluster at the nuclear surface. However, in conventional cluster models, inner clusters are usually assumed and the cluster excitation effects are not considered. Our final goal is to study the $^{28}\text{Si}+\alpha$ excited states of ^{32}S . To this end, for the first step, we investigate the structure change of the ^{28}Si core and the α -cluster breaking in the $^{28}\text{Si}+\alpha$ cluster structure.

2. Framework

We apply extended cluster model to take into account the structure change of the ^{28}Si core and the α -cluster breaking. We first explain Brink-Bloch α -cluster model (conventional cluster model) [7], and later, we describe the extended model for treating the α -cluster breaking and the structure change of the ^{28}Si core.



2.1. Brink-Bloch α -cluster model

In the Brink-Bloch α -cluster model [7], each single-particle wave function φ_i is expressed by a Gaussian wave packet:

$$\varphi_i = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{4}} \exp\left[-\nu(\mathbf{r} - \mathbf{R}_i)^2\right] \chi_i \tau_i, \quad (1)$$

where χ_i is the spin part, τ_i is the isospin part, \mathbf{R}_i is the center of the Gaussian wave packet, and ν is the width parameter. An α -cluster is described four nucleons (spin up neutron and proton and spin down neutron and proton) expressed by the Gaussian wave packets at the same position. The total wave function Φ of A -particle system is described by the antisymmetrized single-particle wave functions of α -clusters.

$$\Phi = \mathcal{A}[\varphi_1 \cdots \varphi_A], \quad (2)$$

where \mathcal{A} is the antisymmetrizing operator.

2.2. Extended cluster model with α -cluster breaking

For description of the α -cluster breaking, we apply the method proposed by Itagaki et al [8] to introduce the effect of the spin-orbit potential. In this method, a parameter is introduced to break the α -cluster so as to gain the spin-orbit interaction. We add a momentum to nucleons of the α -cluster that fixes vertical direction with spin and \mathbf{R}_i .

$$\mathbf{R}_i \rightarrow \tilde{\mathbf{R}}_i = \mathbf{R}_i + i\lambda_\alpha \frac{(\mathbf{e}_{spin,i}) \times (\mathbf{e}_{R_i})}{\sqrt{\nu}}, \quad (3)$$

where λ_α represents the degree of α -cluster breaking. If λ_α is zero, this model becomes the conventional cluster model and describes the intrinsic spin saturated state, where the expectation value of the spin-orbit interaction vanishes. When λ_α is positive, spin-up and spin-down nucleons in the α -cluster have finite momenta with the opposite directions so as to gain the spin-orbit interaction, and the α -cluster has breaking. Indeed for a finite positive value of λ_α , the single nucleons in the α -clusters are boosted to have angular momentum parallel to their intrinsic spin, and therefore they feel the spin-orbit interaction from the core attractively.

2.3. Extended cluster model with structure change of ^{28}Si core

To describe ^{28}Si core and its structure change we adopt the extended 7α -cluster model where the parameter Λ_c for the cluster breaking is incorporated to take into account the spin-orbit interaction effect. The present extended 7α -cluster Brink model is based on the studies of ^{28}Si with the Brink-Bloch 7α -cluster model [9] and also with the AMD (antisymmetrized molecular dynamics) method [10]. This extended 7α -cluster Brink model can describe both the jj -coupling shell model limit at $\Lambda_c = 1$ that is described the spherical $(0d_{5/2})^{12}$ configuration, and the oblate deformation limit of the shell model configuration at $\Lambda_c = 0$.

3. Results

Using the extended cluster model, the energy expectation value of a $^{28}\text{Si}+\alpha$ system is calculated as a function of the inter-cluster distance (R). By analyzing the Λ_c and λ_α dependence of the energy, we investigate how the core structure change and the α -cluster breaking affect to the energy of the $^{28}\text{Si}+\alpha$ system. The total wave function of the extended cluster model is projected to the $J^\pi = 0^+$ state. As for the effective nuclear interaction, the Volkov No. 2 (Majorana parameter $M = 0.67$) [11] for the central force and G3SR ($V = 2000$ MeV) [12] for the spin-orbit force are adopted. The Coulomb force is approximated seven range Gaussians.

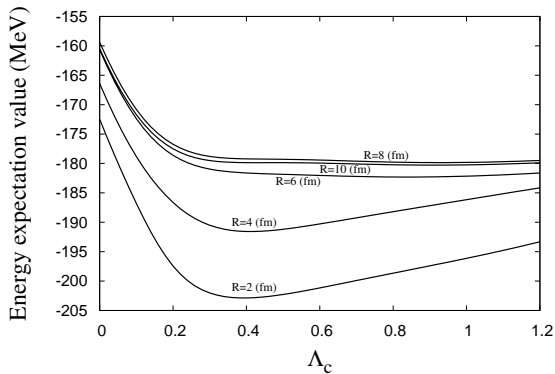


Figure 1. Energy expectation value of $^{28}\text{Si}+\alpha$ as a function of Λ_c for the structure change of the ^{28}Si core. Lines show the energies for the inter-cluster distance $R=2, 4, 6, 8, 10$ fm.

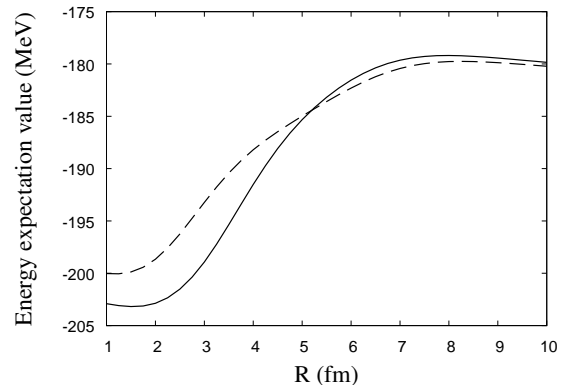


Figure 2. Energy expectation value of $^{28}\text{Si}+\alpha$ as a function of the inter-cluster distance R . The parameter Λ_c for the ^{28}Si -cluster is fixed to $\Lambda_c=0.38$ (oblate-type:solid) and $\Lambda_c=0.80$ (spherical-type:dashed).

3.1. Structure change of ^{28}Si core

We here discuss the calculation without the α -cluster breaking ($\lambda_\alpha = 0$) to focus only on the structure change of the ^{28}Si core. We show the energy expectation value of $^{28}\text{Si}+\alpha$ as a function of the parameter Λ_c for the structure change of the ^{28}Si core in Fig.1. It is found that, in the case of the large inter-cluster distance $R = 8, 10$ fm, the energy almost degenerates in a wide Λ_c region of $\Lambda_c \geq 0.3$ because the oblate and spherical states degenerate in the isolate ^{28}Si without an α -cluster. On the other hand, in the small R region, the oblate deformed ^{28}Si core (around $\Lambda_c = 0.38$) tends to be energetically favored than the spherical ^{28}Si core. This suggests that the core structure change occurs when the α -cluster exists at the surface of the ^{28}Si core. The origin structure change of the ^{28}Si core can be understood by the Pauli blocking effect. Namely, the ^{28}Si core favors to deform oblate to avoid overlapping with the α -cluster at the surface.

We also show the energy expectation value of $^{28}\text{Si}+\alpha$ as a function of the inter-cluster distance R in Fig.2. Here the energies for the fixed ^{28}Si core cases of the oblate ^{28}Si with $\Lambda_c=0.38$ and the spherical ^{28}Si with $\Lambda_c=0.80$ are shown. As mentioned above, the oblate deformed ^{28}Si core is favored than the spherical state in the small R region, while they almost degenerate to each other at the large distance region.

If the α -cluster excited states exist in ^{32}S , they are expected to have the α -cluster amplitude at the nuclear surface. The present result suggests that the structure change of the ^{28}Si core may occur because of the α -cluster at the surface and it may give some effect on the α -cluster excited state of ^{32}S .

3.2. α -cluster breaking

We investigate the α -cluster breaking effect on the energy expectation value of $^{28}\text{Si}+\alpha$ by analyzing the λ_α dependence of the energy. For $^{28}\text{Si}+\alpha$ with a fixed inter-cluster distance R , the optimized λ_α for the minimum energy is small as $\lambda_\alpha \sim 0$ in $R > 3$ fm region indicating that the α -cluster breaking may be a minor effect in $^{28}\text{Si}+\alpha$ system (hardly energy difference at $R \geq 4$ region). The reason for the unflavored α -cluster breaking is as follows. In general, in the mechanism of the α -cluster breaking caused by the spin-orbit potential at the nuclear surface, nucleons in the α -cluster occupy ls -favored orbits rather than to form the α -cluster. However, in the $^{28}\text{Si}+\alpha$ system, nucleons in the ^{28}Si core already fill the ls -favored orbits, $0d_{5/2}$ orbits, and

they block the α -cluster breaking. In other words, the α -cluster breaking tends to be suppressed at the surface of the ^{28}Si core because of the Pauli blocking effect from the core nucleons.

4. Summary and outlook

We calculate the energy expectation value of a $^{28}\text{Si}+\alpha$ system using the extended cluster model. By analyzing the core structure change and the α -cluster breaking in the $^{28}\text{Si}+\alpha$ system, we found that the structure change of the ^{28}Si core is energetically rather important while the α -cluster breaking is not significant when the α -cluster exists at the surface of the ^{28}Si core. In the ^{28}Si core, the oblatelly deformed state tends to be favored than the spherical sub-shell closed state because of the α -cluster at the surface though they almost degenerate in the isolate ^{28}Si without an α -cluster. We also found that the degree of α -cluster breaking depends on the core nuclei and it is minor in $^{28}\text{Si}+\alpha$ system compared with $^{16}\text{O}+\alpha$ system. The present result suggest that the structure change of the ^{28}Si cluster may give important effect on the α -cluster excited state of ^{32}S and that the α -cluster breaking effect may be relatively minor. We are now proceeding to perform further calculations of the generator coordinate method by superposing the $^{28}\text{Si}+\alpha$ wave functions to study the α -cluster excited states of ^{32}S .

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