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Cluster Thomas-Ehrman Shift in ^{10}Be–^{10}C

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Abstract

Coulomb shift of the ^{10}Be and ^{10}C nuclei, which can be nicely described by the $\alpha + \alpha + N + N$ four-body degrees of freedom, is investigated by the microscopic cluster model. The Coulomb shift is prominent for the non S-wave configurations, while the shift is suppressed for the S-wave dominant configurations, which have the well-developed α cluster structure. This result can be interpreted in terms of the so-called Thomas-Ehrman shift, which is originally discussed in the Coulomb shift of the ^{17}O–^{17}F systems.

1 Introduction

In light neutron-excess systems, many kinds of molecular structures are discussed from the viewpoint of the clustering phenomena. In particular, much attention has been concentrated on Be isotopes from the theoretical and experimental approaches. The Be isotopes can be considered as typical examples of two-center superdeformed systems which build on an $\alpha + \alpha$ rotor of ^{8}Be. Various cluster structures are generated by the coupling the two α degrees of freedom and the single particle motion of the excess neutrons, and the structures are analogous to the so-called chemical-bonding structure in molecular systems.

The low-lying states can be nicely understood by the molecular orbital (MO) picture, in which the excess neutrons perform the single-particle motion in the π^- or σ^+ orbitals around two α cores [1]. The σ^+ orbit, which has a large mixture of the S-wave component, enhances the α–α clustering.

On the contrary, in their highly-excited states, recent experiments revealed the existence of the interesting resonant states, which dominantly decay into the ^{4,6,8}He fragments [2,3]. These resonances are interpreted in terms of the ionic or atomic configurations of ^{x}He + ^{y}He, in which neutrons are trapped in one of the α cores and generates the exchange force [4, 5].

The systematic studies of the chemical-bonding structure identified in Be isotopes is very interesting. One of the systematic studies is the analysis of the mirror systems, and the Coulomb shift in the proton-rich side is an interesting research subject. For example, a typical example of the Coulomb phenomena is known as the so-called Thomas-Ehrman shift (TES), which was originally discussed in the mirror systems, such as the ^{17}O and ^{17}F nuclei [6]. In the ^{16}O core plus one nucleon model, the Coulomb shift in ^{17}F = ^{16}O + P is exceptionally suppressed for the S-wave orbit although the Coulomb shift occurs uniformly for other non S-wave orbits. The S-wave proton can escape from the Coulomb repulsion because of no centrifugal barrier, which tends to confine the wave function inside of the Coulomb barrier.

One of the characteristic features in cluster structure is the spatial extension, which involves the S-wave dominance. In the covalent configurations, for example, the σ^{+} orbit with a large mixture of the S-wave component enhance the α clustering, while two nuclei dominantly perform the S-wave relative motion in the atomic or ionic configurations. These cluster picture strongly suggests that the development of the clustering involves the suppression of the Coulomb shift. In this report, the Coulomb shift of ^{10}Be–^{10}C is investigated, which are typical example of the nuclear chemical-bonding systems [5].

We apply the generalized two-center cluster model (GTCM) [4, 5] to ^{10}Be (= $\alpha + \alpha + 2N$) and ^{10}C (= $\alpha + \alpha + 2P$). This model is available to handle the formations of the covalent MOs and the ionic or atomic structures in a unified manner. Therefore, the Coulomb shift can be discussed in connection to the structural changes from the low-lying covalent structures to the highly-excited atomic structure.

2 Framework

The detailed explanation of GTCM has already been published in Refs. [4,5], and we briefly explain the formulation of GTCM in the following. In this model, the basis functions of ^{10}Be = $\alpha + \alpha + 2N$ and ^{10}C = $\alpha + \alpha + 2P$

are given by the $\{\Phi_{\mathbf{m}}^{J^\pi K}(S)\}$, where,

$$\Phi_{\mathbf{m}}^{J^\pi K}(S) = \hat{P}_K^{J^\pi} \mathcal{A} \left\{ \psi_L(\alpha)\psi_R(\alpha) \prod_{j=1}^{2} \varphi_j(m_j) \right\}_S . \quad (1)$$

The α-clusters at the left (L) and right (R) side center are shown by $\psi_i(\alpha)$ ($i = L, R$), and they are placed with a relative distance parameter of S, which is the generator coordinate [7]. The internal structure of the α clusters are expressed by the $(0s)^4$ configurations of the harmonic oscillator (HO). The single-particle wave function for the valence nucleons localized around the α clusters is given by an atomic orbital (AO) $\varphi(m_j)$, which is labeled by the AO indices of $m_j = (p_k, i, \tau)$. Here, p_k ($k = x$, y, z) means the $0p$-orbitals around i-th core ($i = L$ or R) with the spin τ ($= \uparrow$ or $\downarrow$). In Eq. (1), $\mathbf{m}$ represents a set of AOs for the valence nucleons, $\mathbf{m}$=(m_1, m_2). The intrinsic basis functions with the full anti-symmetrization $\mathcal{A}$ are projected to the eigenstate of the total spin J, its intrinsic angular projection K, and the total parity π by the projection operator $\hat{P}_K^{J^\pi}$.

The total wave function is finally given by taking the superposition over S, $\mathbf{m}$ and K as

$$\hat{\Psi}_\nu^{J^\pi} = \int dS \sum_{\mathbf{m},K} C_{\mathbf{m}K}^{\nu}(S)\, \Phi_{\mathbf{m}}^{J^\pi K}(S) . \quad (2)$$

The coefficients for the ν-th eigenstate, $C_{\mathbf{m}K}^{\nu}(S)$, are determined by solving a coupled-channel GCM (Generator Coordinate Method) equation [7]. In the present calculation, we consider all the possible $0p$ atomic-orbit configurations, which lseads to the complete formation of the covalent, ionic, and atomic configurations around two α cores.

As for the nucleon-nucleon (NN) interaction, we use the Volkov No.2 [8] and the G3RS [9] for the central and spin-orbit parts, respectively. In ^{10}Be, the parameters in the interactions and the size parameter of HO are the same as those applied in the analysis of ^{10,12}Be [4, 5]. On the contrary, the NN interactions are slightly modified in ^{10}C so as to reproduce the α + ^{6}Be threshold energy. The majorana parameter (M) in ^{10}C is increased by about 20 % in comparison to the parameter in ^{10}Be.

In the present calculation, all of the excited states are calculated by the bound state approximation although the treatment of the scattering problem is also available [4, 5]. The analysis of the scattering states will be shown in future studies.

3 Results

Figure 1 shows the energy levels of ^{10}Be (left levels) and ^{10}C (right levels). In the individual spectra, the lowest four 0^+ levels are plotted. The dominant components of the 0^+_1 and 0^+_2 states are the molecular orbit configuration of $(\pi^-_{3/2})^2$ and $(\sigma^+_{1/2})^2$, respectively, in which two valence nucleons performed the single particle motion around two α cores. On the contrary, the unbound 0^+_3 and 0^+_4 states have the atomic configurations of the $\alpha + {}^6\mathrm{He}_{g.s.}$ and $\alpha + {}^6\mathrm{He}(2^+)$, respectively.

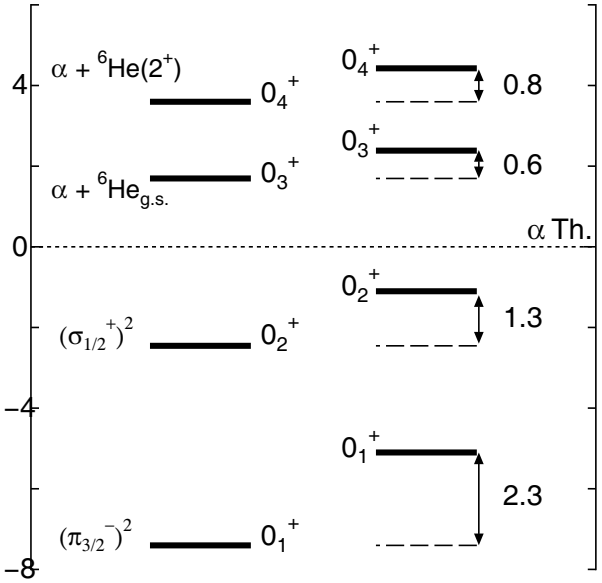

Figure 1: Energy levels of the ^{10}Be (left levels) and ^{10}C (right levels) nuclei. The α threshold is set to be zero energy. In the ^{10}C spectra, the corresponding levels to ^{10}Be are plotted by the dashed line. The numbers attached to the levels show the energies of the Coulomb shifts. The Coulomb shifts are shown in units of MeV.

In the ^{10}C spectra, the Coulomb shifts to the higher energy region are confirmed, and the magnitude of the shifts depend on the energy levels. The shift of the 0^+_1 state is 2.3 MeV, which is the largest of all the energy levels. This prominent shift is due to the spatially compact structure of the $(\pi^-_{3/2})^2$ configuration. The $\pi^-_{3/2}$ orbit, which has a main component of the P-wave orbit, strongly reduce the α-α distance, and the 0^+_1 state has a spatially compact structure similar to the shell model-like structure. Therefore, the effect of the Coulomb repulsion is prominent for the compact 0^+_1 state in the

proton-rich side, the ^{10}C nucleus.

On the contrary, the Coulomb shift of the 0_2^+ state is 1.3 MeV, which is smaller than the shift of the ground 0_1^+ state, 2.3 MeV. The reduction of the shift for 0_2^+ is due to the spatially extended structure of the $\sigma_{1/2}^+$ orbit, which has a large mixture of the S-wave component. The large mixing of the S-wave component in the valence orbit leads to the enhancement of the α-α clustering. Since the repulsive effect of the Coulomb interaction is reduced in the spatially extended configuration, the Coulomb shift for the 0_2^+ state is suppressed in comparison to the shift for the 0_1^+ state.

Moreover, the Coulomb shifts for the 0_3^+ and 0_4^+ states are suppressed much more, which are 0.6 MeV and 0.8 MeV, respectively. This reduction is generated by the well-developed binary cluster structures of α + ^{6}He, which makes it possible to escape from the Coulomb repulsion. In the 0_3^+ state, the α and $^6\mathrm{He}_{g.s.}$ perform the S-wave relative motion, while the α + $^6\mathrm{He}(2^+)$ with the D-wave relative motion is a main component in the 0_4^+ state. Since the S-wave component is predominant in 0_3^+, its Coulomb shift is suppressed in comparison to the 0_4^+ state.

In all the spectra, the Coulomb shift is reduced for the S-wave dominant states (0_2^+ and 0_3^+), while the shift is enhanced for the respective non S-wave states (0_1^+ and 0_4^+). Therefore, these suppressed Coulomb shift for the S-wave states are basically same as the Thomas-Ehrman Shift, which was originally discussed in the ^{17}O and ^{17}F systems [6]. The Coulomb suppression in ^{10}Be and ^{10}C, which are shown in Fig. 1, correspond to the extension of the Thomas-Ehrman Shift to the cluster degrees of freedom, which is induced by the $\alpha + \alpha + 2N$ structure.

4 Summary and discussion

We have applied the generalized two-center cluster model to the mirror systems, such as $^{10}\mathrm{Be} = \alpha + \alpha + 2N$ and $^{10}\mathrm{C} = \alpha + \alpha + 2P$, and discussed the Coulomb shift in the lowest four 0^+ states. The present calculation predicts the suppression of the Coulomb shift for the S-wave dominant state, which is generated by the development of the α clustering. Thus, the suppressed Coulomb shift presented here should be called the "Cluster Thomas-Ehrman Shift", which corresponds to the extension of the traditional Thomas-Ehrman Shift on the single particle motion.

In the present calculation, we have employed the bound state approximation for the unbound states above the α decay threshold. In our previous analysis on the continuum state [4, 5], the 0_3^+ state in ^{10}Be, which has a

developed $\alpha + {}^6\mathrm{He}_{g.s.}$ structure, is not a sharp resonant states but a broad continuum-like state, while the 0_4^+ state is a resonance. This result is consistent to the recent experiment of the ^{6}He scattering by the α target [10]. Therefore, the Coulomb shift in the continuum states should be carefully discussed by employing the scattering boundary condition. The calculation with the scattering boundary condition is now underway.

Furthermore, the present calculation also predicts the asymmetry in the monopole transition from 0_1^+ to 0_2^+; specifically, the $0_1^+ \to 0_2^+$ strength in ^{10}C is about twice as large as the respective strength in ^{10}Be. Due to the suppression of the Coulomb shift for the 0_2^+ state, the excitation energy of 0_2^+ in ^{10}C is reduced in comparison to the respective excitation energy in ^{10}Be. This reduction leads to the enhancement of the monopole transition in ^{10}C. The detailed analysis of the monopole transitions will be shown in forthcoming papers.

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