Dineutron Formation and Breaking in $^8$He

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Received: 25 October 2013 / Accepted: 11 February 2014 / Published online: 8 March 2014
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Abstract We investigate the structures of the $0^+$ states in $^8$He from the viewpoint of dineutron correlation, i.e., spatial correlation between two neutrons coupled to a spin singlet. In this paper, we mainly discuss the $0^+_2$ state which is a candidate for the two-dineutron condensate state. This state has one $\alpha$ and two compact dineutrons expanded widely with little correlation with each other to form a gaslike structure.

1 Introduction

In neutron-rich nuclei, a lot of exotic phenomena have been suggested so far. Dineutron correlation is one of the most interesting topics in the physics of neutron-rich nuclei. A dineutron is a spin-singlet pair of two neutrons. As is well known, two neutrons are not bound in free space. However, it is theoretically suggested that the correlation between two neutrons becomes stronger and a compact dineutron can be formed in such situations as a low-density region of nuclear matter and a neutron-halo and -skin region of neutron-rich nuclei. A dineutron becomes compact in some situations and can be considered as a kind of cluster (quasi-boson). It is expected that some dineutrons might form a cluster condensate state, that is, a state containing some identical clusters in the lowest $S$ wave. We are interested in the formation mechanism of a dineutron condensate (DC) state and the properties of dineutrons in such a state. In this paper, we focus on $^8$He, which is well described with an $\alpha$ core plus four valence neutrons, and mainly discuss the excited $0^+$ state containing one $\alpha$ and two compact dineutron clusters spatially distant. We suggest that this state is a two-dineutron condensate state. In $^8$He, which has four valence neutrons, the component of $\nu((0p_3/2)^4$ sub-shell closure and the one of one or two developed dineutrons are expected to be significant. After taking into account these configurations sufficiently, we investigate the possibility of the dineutron condensation in $^8$He. To describe those configurations, we superpose two kinds of wave functions, that is, the extended $^6$He + $2n$ wave function and the $^8$He DC wave function [1,2]. In the former, we can describe the harmonic oscillator shell-model component such as $(0p_3/2)^4$. In the latter, we can describe the motion of dineutrons about a core. We describe the component of one or two developed dineutrons with the DC wave function. In this paper, we consider $0^+$ states described by superposing these wave functions, and we discuss the $0^+$ states, mainly the excited $0^+$ state.

2 Framework

We superpose two kinds of wave functions to describe $^8$He $(0^+)$ states, the extended $^6$He + $2n$ cluster wave function and the $^8$He DC wave function. We project the those wave functions to $J^\pi = 0^+$, and we diagonalize the Hamiltonian by using those wave functions to obtain the $0^+$ states. In the following, we explain these frameworks briefly.

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2.1 Extended $^6$He + 2$n^*$ Cluster Wave Function

The extended $^6$He + 2$n^*$ cluster wave function describes $^8$He as a system of $^6$He plus extended 2$n$ (denoted as 2$n^*$ hereafter) clusters. The $^6$He cluster is composed of an $\alpha$ cluster and two valence neutrons in (0$p$)2 orbits around the $\alpha$. We describe the valence neutrons with a shifted Gaussian from the $\alpha$ particle. We locate the extended 2$n$ cluster around $^6$He described in such a way. By “extended”, we mean that we take into account the dissociation of the 2$n$ cluster due to the spin-orbit interaction. In the ordinary cluster wave function, the single-particle wave function is a Gaussian which have a real center parameter. A real part of the Gaussian center corresponds to the mean position of the nucleon. In the present one, we add an imaginary part, $\lambda$, to each Gaussian center as done in Ref. [3]. An imaginary part corresponds to the mean momentum of the nucleon. When $\lambda = 0$, the 2$n^*$ cluster is a spin-singlet cluster, that is, a dineutron. When $\lambda \neq 0$, the spin-up and spin-down neutrons in the 2$n^*$ cluster have the opposite momentum to gain the spin-orbit attraction. Then, the 2$n^*$ cluster is not a spin-singlet cluster any longer exactly. In this way, we take into account the dissociation of spin-singlet pairs and describe the configurations such as ($0p_{3/2}$)$^4$. The form of the $^6$He + 2$n^*$ cluster wave function is as follows.

$$\Phi_{^6\text{He}+2n^*} = A\left\{\Phi_0^{^6\text{He}}(R_{^6\text{He}}, b_\alpha) \phi_{n\uparrow}(R_{\uparrow}, b_\alpha) \phi_{n\downarrow}(R_{\downarrow}, b_\alpha)\right\}. \quad (1)$$

$\Phi_0^{^6\text{He}}$ and $\phi_{n\uparrow/\downarrow}$ are the wave functions of the $^6$He cluster and the spin-up/down valence neutrons. $R$ is the Gaussian centers, $R_{^6\text{He}} = (-1/4d_\lambda, 0, 0)$ and $R_{\uparrow/\downarrow} = (3/4d_\lambda, \pm i\lambda, 0)$. $b_\alpha = 1.46$ fm is the Gaussian width and common to all the nucleons in this wave function. In this work, we superpose the wave functions with $\lambda = 0, 0.4$ fm and $d_\lambda = 1, \ldots, 4$ fm.

2.2 $^8$He DC Wave Function

The DC wave function describes a system of a core plus one or a few dineutrons in the $S$ wave around the core. In the present work, the core is $\alpha$ + 2$n^*$ and one dineutron is distributed around the core. The form of the wave function is

$$\Phi_{\text{DC}} = A\left\{\Phi_\alpha(R_\alpha, b_\alpha) \phi_{n\uparrow}(R_{\uparrow}, b_\alpha) \phi_{n\downarrow}(R_{\downarrow}, b_\alpha) \times \psi_r(b_n) \psi_G(\beta)\right\}, \quad (2)$$

$$\psi_r \propto \exp\left[-\frac{r^2}{4b^2_n}\right], \quad \psi_G \propto \exp\left[-\frac{r^2}{\beta^2}\right], \quad (3)$$

where $\Phi_\alpha \phi_{n\uparrow} \phi_{n\downarrow}$ is the core wave function of $\alpha$ + 2$n^*$. $\psi_r$ and $\psi_G$ are the relative and center-of-mass parts of the dineutron wave function composed of two neutrons coupled to a spin singlet. They have the relative coordinate between the two neutrons, $r$, and the center-of-mass coordinate of the two neutrons, $r_G$, respectively. In the relative part, the Gaussian width is $b_n$ and this parameter characterizes the relative distance between two neutrons, i.e., the dineutron size. In the center-of-mass part, the Gaussian width is $\beta$ and characterizes the distance between the center of mass of the two neutrons and that of the core, i.e., the spatial expansion of the dineutron from the core. In the DC wave function, we vary these parameters to describe a state containing a dineutron with various sizes and distributions. We superpose the DC wave functions with $\beta = 0, 0.2, \ldots, 8$ fm and five $b_n$ values for each $\beta$. We prepare two kinds of parameter sets characterizing the $\alpha$ + 2$n^*$ core, that is, $\lambda = 0$ fm and $d_\lambda = 1, \ldots, 8$ fm and $b_n = b_n$, and $\lambda = 0.4$ fm and $d_\lambda = 1, \ldots, 4$ fm and $b_n = b_n$. In the former set, the 2$n^*$ cluster is also a dineutron and has the same size as the other dineutron and they can be expanded widely. In the latter, the 2$n^*$ cluster is dissociated at the surface of the $\alpha$. Superposing these DC wave functions, we describe the configurations such as $\alpha$ + 2$n([0p_{3/2}]^2) +$ one developed dineutron and two-dineutron condensation where two dineutrons have the same compact size and both are in the lowest $S$ wave.

3 Results

We discuss the $0^+$ states described by superposing the wave functions explained in Sect. 2. For the Hamiltonian in the present calculation, we use the effective two-body interactions, namely the Volkov No.2 force as the central force and the spin-orbit part of the G3RS force as the spin-orbit force. The parameters in the central
Table 1 Energies and matter, proton and neutron radii \((r_m, r_p, \text{and } r_n)\) in the \(0^+_{1,2}\) states

| State     | Energy (MeV) | \(r_m\) (fm) | \(r_p\) (fm) | \(r_n\) (fm) |
|-----------|--------------|--------------|--------------|--------------|
| \(0^+\)  | −31.13       | 2.37         | 1.87         | 2.51         |
| \(0^+\) (Expt.) | −31.40       | 2.49–2.52    | 1.76–2.15    | 2.64–2.69    |
| \(0^+_2\) | −23.24       | 4.85         | 2.26         | 5.44         |

As for \(0^+\), we show the experimental values in the second line.

3.1 Energies and Radii of \(0^+_{1,2}\)

We calculate the energy and the matter, proton and neutron radii of the \(0^+_{1,2}\) states shown in Table 1. The \(0^+\) energy agrees with the experimental value. Although the neutron radius of the \(0^+\) state is underestimated compared with the experimental value, the large difference between the proton and neutron radii, which means a neutron skin, is well reproduced in the present calculation. We skip the details of the structure of the \(0^+\) state, but the \((0p3j_2)^4\) and one-dineutron components are important in this state. In the \(0^+_{2}\) state, whose excitation energy is \(\sim 8\) MeV, the neutron radius is much larger than that of the \(0^+\) state. This means that the valence neutrons extend to large distances in this state. In the next subsection, we suggest that this state has a gaslike structure of one \(\alpha\) and two compact dineutrons and that it is the two-dineutron condensate state.

3.2 Dineutron Component in the \(0^+_2\) State

To see the two-dineutron component in the \(0^+_2\) state, we calculate the overlap with the DC wave function containing one \(\alpha\) and two spin-singlet pairs of two neutrons.

\[
N_{\text{dineutron}}(\beta, b_n) = |\langle \Phi_{2\text{DC}}(\beta, b_n)|\Psi_{8\text{He}(0^+_2)} \rangle|^2, \tag{4}
\]

where \(\Psi_{8\text{He}(0^+_2)}\) is the wave function of the \(0^+_2\) state described by superposing the \(6\text{He} + 2n^+\) wave functions and \(8\text{He}\) DC wave functions. \(\Phi_{2\text{DC}}\) is the test DC wave function describing the system containing two dineutrons which have the same size, \(b_n\), and expansion from the core, \(\beta\). These two dineutrons are distributed around the core in the \(S\) wave as Eq. (2), so this wave function with small \(b_n\) and large \(\beta\) corresponds to the component of two-dineutron condensation, which means that two compact dineutrons considered as a kind of cluster are in the lowest \(S\) wave and expanded widely. We plot the overlap with \(\Phi_{2\text{DC}}\) as a function of the dineutron size, \(b_n\), and its spatial expansion from the core, \(\beta\), in Fig. 1. A peak exists at \((\beta, b_n) \sim (5, 2)\) with a broad width in both the direction of \(\beta\) and \(b_n\). The peak value of \(b_n \sim 2\) fm is much smaller than the size of the total system, and, therefore, the valence neutrons in this state form two compact dineutrons. However, this peak has the broad width in the \(b_n\) direction (the peak spreads from \(\sim 1.5\) to \(\sim 3\) fm), which means that these dineutrons are certainly compact but their size changes readily. The broad width in the \(\beta\) direction (the peak spreads from \(\sim 3\) to \(\sim 7\) fm) means that the interaction between the \(\alpha\) and two dineutron clusters is weak and that these clusters are expanded widely. This corresponds to the gaslike structure of one \(\alpha\) and two dineutrons.

4 Summary

In this paper, we have mainly reported the possibility of the existence of the two-dineutron condensation in the excited state of \(8\text{He}\). The candidate has a much larger neutron radius than that of the ground state and the four.
Valence neutrons are very spatially extended. They form two spin-singlet pairs and they become compact to be a dineutron. We have shown that, in that state, two dineutrons are rather compact but soft in size changing. These two dineutrons are expanded spatially from the core keeping a compact size, and one $\alpha$ and two dineutron clusters have little correlation with each other to form a gaslike structure of $\alpha$+two dineutrons.

Two neutrons are not bound in free space, so a dineutron is naturally soft and changes its size readily, especially in such low-density structure as the gas-like one of the $0^+_2$ state. However, it is sure that a dineutron becomes so small that it can behave as a kind of cluster, and it is expected that a dineutron condensation can be realized in neutron-rich nuclei. It is challenging to investigate neutron-rich nuclei systematically in view of the dineutron condensation and to make clear the universal properties of the dineutron in such a system.

Acknowledgments This work was supported by Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science (JSPS). It was also supported by the Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. A part of the computational calculations of this work was performed by using the supercomputers at YITP.

References
1. Kobayashi, F., Kanada-En’yo, Y.: A new approach to investigate dineutron correlation and its application to $^{10}$Be. Prog. Theor. Phys. 126, 457 (2011)
2. Kobayashi, F., Kanada-En’yo, Y.: Dineutron formation and breaking in $^8$He. Phys. Rev. C 88, 034321 (2013)
3. Itagaki, N., Masui, M., Ito, M., Aoyama, S.: Simplified modeling of cluster-shell competition. Phys. Rev. C 71, 064307 (2005)