Two Neutron Correlations in Exotic Nuclei

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Abstract. We study the correlations between two neutrons in borromian nuclei ^{11}Li and ^{6}He by using a three-body model with a density-dependent contact two-body interaction. It is shown that the two neutrons show a compact bound feature at the nuclear surface due to the mixing of single particle states of different parity. We study the Coulomb breakup cross sections of ^{11}Li and ^{6}He using the same three-body model. We show that the concentration of the B(E1) strength near the threshold can be well reproduced with this model as a typical nature of the halo nuclei. The energy distributions of two emitted neutrons from dipole excitations are also studied using the correlated wave functions of dipole excitations.

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It has been well recognized by now that the borromian nuclei such as ^{11}Li and ^{6}He show a strong di-neutron correlations in the ground states and also in the excited states. Recently, Nakamura *et al.* have remeasured the low-lying dipole excitations in ^{11}Li nucleus and have confirmed the strong concentration of the dipole strength near the threshold in the 2-neutron (2n) halo nucleus [1]. The low-lying dipole strength for another 2n halo nucleus, ^{6}He, has also been measured by Aumann *et al.* [2]. The two neutron correlations are further measured very recently in the Coulomb breakup process of dipole excitaitons in ^{11}Li [3].

The aim of this paper is to study the correlations between di-neutrons and also neutron-core correlations in borromian nuclei ^{6}He and ^{11}Li by using a three-body model [4, 5, 6]. In Ref. [7], the behavior of the two valence neutrons in ^{11}Li is studied at various positions from the center to the surface of the nucleus. It was found that the two-neutron wave function oscillates near the center whereas it becomes similar to that for a compact bound state around the nuclear surface, and the mean distance between the valence neutrons has a well pronounced minimum around the nuclear surface. We have pointed out that these are qualitatively the same behaviors as found in neutron matter [8]. To elucidate these points, we show in Fig. 1 the mean distance of the valence neutrons in ^{11}Li as a function of the nuclear radius R (the distance between the core and the center of two neutrons) obtained with and without the neutron-neutron (nn) interaction. For the uncorrelated calculations, we consider both the $[(1p_{1/2})^2]$ and $[(2s_{1/2})^2]$ configurations. One can see that, in the non-interacting case, the neutron pair almost monotonously expands, as it gets further away from the center of the nucleus. On the other hand, in the interacting case it first becomes smaller going from inside to the surface before expanding again into the free space configuration. These results confirm the strong and predominant influence of the pairing force in the nuclear surface of^{11}Li. We also show

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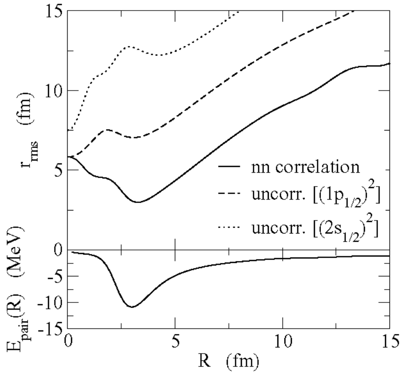

FIGURE 1. Upper panel: the root mean square distance $r_{\rm rms}$ between the valence neutrons in ^{11}Li as a function of the distance R between the core and the center of two neutrons. The solid line is obtained by taking into account the neutron-neutron correlations, while the dashed and the dotted lines are obtained by switching off the neutron-neutron interaction and assuming the $[(1p_{1/2})^2]$ and $[(2s_{1/2})^2]$ configurations, respectively. Lower panel: the neutron-neutron correlation energy as a function of the distance R.

the local neutron-neutron correlation energy as a function of the radius R in the lower panel of Fig. 1. It is clearly seen that the energy gain is the maximum at the surface where the correlaiton length is the minimum. The two panels in Fig. 1 confirm that the kink of the correlation length is induced by the strong pairing correlations at the surface.

Two particle densities of the correlated pair and the uncorrelated $[(1p_{1/2})^2]$ configuration are shown in Fig. 2. The reference particle is located at $(z,x) = (3.4,0)$fm. As can be seen in the right panel, the distribution has a symmetric two peaks in (z,x) plane with respect to the center of the core nucleus at $(z,x) = (0,0)$fm. This is due to the absence of mixing of opposite parity wave functions into the $[(1p_{1/2})^2]$ configuration. On the contrary, the peak appears only around the position of the reference particle when the two neutron correlations are taken into account in the wave functions. To compare two panels in Fig. 2, we can see a clear manifestation of the strong two neutron correlations in the wave function of the borromian nucleus ^{11}Li.

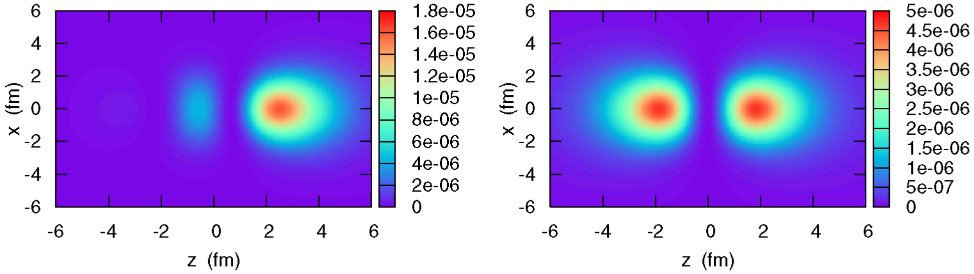

FIGURE 2. (Color online) Two dimensional (2D) plots for the two particle density of the correlated pair (left panel) and uncorrelated $[(1p_{1/2})^2]$ configuration (right panel) in ^{11}Li. It represents the probability distributions for the spin-up neutron placing the spin-down neutron at (z,x)=(3.4,0)fm. The core nucleus is located at the origin (z,x)=(0,0)fm.

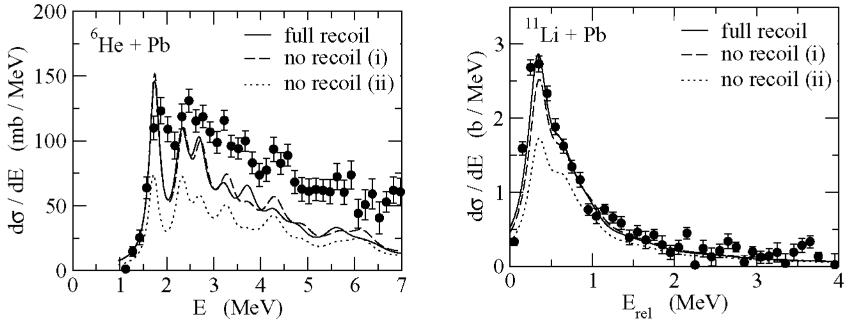

FIGURE 3. Coulomb breakup cross sections for ^{6}He+Pb at 240 MeV /nucleon and for the ^{11}Li +Pb at 70 MeV/nucleon. The solid line is the result of the full calculations, while the dashed line is obtained by neglecting the off-diagonal component of the recoil kinetic energy in the excited states. The dotted line is obtained by neglecting the off-diagonal recoil term both in the ground and the excited states. These results are smeared with an energy dependent width of $\Gamma = 0.15 \cdot \sqrt{E_{\rm rel}}$ MeV for ^{6}He and $\Gamma = 0.25 \cdot \sqrt{E_{\rm rel}}$ MeV for ^{11}Li. The experimental data are taken from Refs. [2] and [1] for ^{6}He and ^{11}Li, respectively.

Figs. 3 compare the Coulomb breakup cross sections calculated by taking into account the recoil term exactly (the solid curves) with those calculated approximately (the dashed and dotted curves). For the dashed curves, the off-diagonal component of the recoil kinetic energy is neglected in the excited $J^\pi = 1^-$ states, while it is fully taken into account in the ground state. It is interesting to notice that these calculations lead to similar results to the one in which the recoil term is treated exactly (the solid curves). The dotted curves, on the other hand, are obtained by neglecting the off-diagonal part of the recoil term both for the ground and the $J^\pi = 1^-$ states. By neglecting the recoil term in the ground state, the value for $\langle r^2_{c-2n} \rangle$ decreases, from 13.2 fm^2 to 9.46 fm^2 for ^{6}He and from 26.3 fm^2 to 20.58 fm^2 for ^{11}Li. Consequently, the B(E1) distribution as well as the breakup cross sections are largely underestimated. These results clearly indicate that the recoil term is important for the ground state, while it has a rather small effect on the excited states.

Figures 4 show the dipole strength distribution, $d^2B(E1)/de_1de_2$, as a function of the energies of the two emitted neutrons for the ^{11}Li and ^{6}He nuclei, respectively [9]. One immediately notices that the strength distribution is considerably different between ^{11}Li and ^{6}He. For ^{11}Li, a large concentration of the strength appears at about e_1=0.375 MeV and e_2=0.075 MeV (and at e_1=0.075 MeV and e_2=0.375 MeV), with a small ridge at an energy of about 0.5 MeV. On the other hand, for ^{6}He, the strength is largely concentrated at one peak around $e_1 = e_2 = 0.7$ MeV and only a large ridge at about 0.7 MeV appears. This difference between ^{11}Li and ^{6}He is due to the existence of virtual s-state in the residual ^{10}Li, but not in ^{5}He. Thus, if the interaction between the neutron and the core nucleus is switched off, the distribution become similar between the two nuclei because the virtual s-state is diappeared in ^{10}Li.

In summary, we have studied the di-neutron correlations and the neutron-core correlations in the borromian nuclei ^{6}He and ^{11}Li by using the three-body model with a density dependent contact interaction. It is shown that the two neutron wave functions show a strong di-nuetron correlation at the nuclear surface due to the mixing of differ-

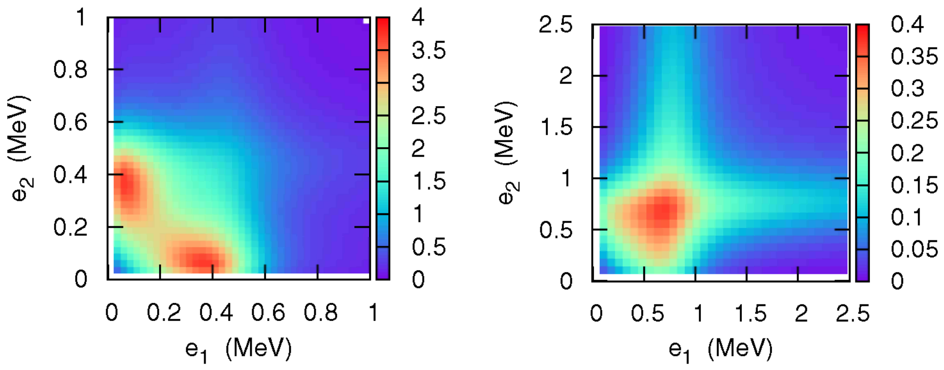

FIGURE 4. (Color online) The dipole strength distributions, $d^2B(E1)/de_1de_2$, of ^{11}Li (left panel) and ^{6}He (right panel) as a function of the energies of the two emitted neutrons relative to the core nucleus. They are plotted in units of e^2fm^2/MeV^2. Figures show the correlated response, which fully takes into account the ground state and final state interactions between the two neutrons.

ent parity single particle states. The same model is used to analyze the dipole strength distributions as well as the Coulomb breakup cross sections of the ^{6}He and ^{11}Li nuclei. We have shown that the strong concentration of the B(E1) strength near the continuum threshold can be well reproduced as a nature of the halo nuclei with the present model. It is shown that the recoil effect plays an important role in the ground state while it may be neglected in the excited states. We have carried out the calculations of the energy and angular distributions of the two emitted neutron from E1 excitations in ^{11}Li and ^{6}He nuclei. We have shown that these distributions are strongly affected by the existence of the virtual s-state in the residual ^{10}Li nucleus. Thus, the properties of the neutron-core potential is crucial to describe the energy distributions of two emitted neutrons, rather than the two neutron correlaions in the excited states.

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