Two-particle correlations in continuum dipole transitions in Borromean nuclei

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Abstract. We use a three-body model to discuss the role of dineutron correlation in the ground state and the dipole excitations of typical weakly-bound Borromean nuclei, $^{11}$Li and $^{6}$He. We first show that the wave function for the neutron pair in the ground state is strongly concentrated on the nuclear surface for both nuclei. We then show that the energy distributions for the two emitted neutrons from the dipole excitation, on the other hand, are considerably different between the two nuclei, even though they show similar strong dineutron correlations in the ground state to each other. Our calculation indicates that this different behaviour of the energy distribution primarily reflects the interaction between the neutron and the core nucleus, rather than the interaction between the valence neutrons.

1. Introduction
Neutron-rich nuclei have attracted much interest during the past decades. These nuclei are characterized by a small binding energy, and many new features originating from the weakly bound property have been found. A halo and skin structures with a large spatial extension of the density distribution, and strong concentration of electric dipole ($E1$) transition at low excitation energies are well-known examples.

Among neutron-rich nuclei, two-neutron halo nuclei are particularly intriguing systems to study. Their structure has often been described as a three-body system consisting of two valence neutrons interacting with each other and with the core nucleus. Some light neutron-rich nuclei, such as $^{11}$Li and $^{6}$He, do not have a bound state in the two-body subsystem with a valence neutron and a core nucleus. These nuclei are referred to as Borromean nuclei, and their properties have been studied extensively both experimentally and theoretically.

One of the most important current open questions concerning the Borromean nuclei is to clarify the characteristic nature of correlations between the two valence neutrons, which do not form a bound state in the vacuum. A strong dineutron correlation, where the two neutrons take a spatially compact configuration, has been theoretically predicted [1, 2, 3, 4, 5, 6]. Although the recent experimental observation of the strong low-lying dipole strength distribution in the $^{11}$Li nucleus [7] has provided an experimental signature of the existence of dineutron correlation in this nucleus, its direct evidence has not yet been obtained.

In this contribution, we present the results of three-body model calculations with a density-dependent contact interaction between the two valence neutrons [4]. We first discuss the dineutron correlation in the ground state of $^{11}$Li and $^{6}$He nuclei, and then consider the dipole excitation of...
these Borromean nuclei. We will particularly discuss the energy distribution of the two emitted neutrons.

2. Ground state properties
Let us first discuss the ground state properties of the $^{11}\text{Li}$ and $^{6}\text{He}$ nuclei. Figs. 1 and 2 show the two-particle density for these nuclei, respectively. These are plotted as a function of the neutron-core distance, $r_1 = r_2 = r$ and the opening angle between the valence neutrons, $\theta_{12}$. A weight of $4\pi r^2 \cdot 2\pi r^2 \sin \theta_{12}$ has been multiplied. See Ref. [4] for the details of the calculations.

We see that a large fraction of two-particle density is concentrated on the region with small opening angle $\theta_{12}$. This is nothing but a manifestation of strong dineutron correlation. We recently pointed out that a similar correlation, that is, the diproton correlation, exists also in proton-rich nuclei, such as $^{17}\text{Ne}$ [8].

Figure 1. The two-particle density for the ground state of $^{11}\text{Li}$ as a function of neutron-core distance, $r_1 = r_2 = r$, and the opening angle between the valence neutrons, $\theta_{12}$. The density is weighted with a factor $8\pi^2 r^4 \sin \theta_{12}$.

Figure 2. The two-particle density for the ground state of $^{6}\text{He}$ as a function of neutron-core distance, $r_1 = r_2 = r$, and the opening angle between the valence neutrons, $\theta_{12}$. The density is weighted with a factor $8\pi^2 r^4 \sin \theta_{12}$.

Figure 3. The root mean square distance $r_{\text{rms}}$ for the neutron Cooper pair in $^{11}\text{Li}$ as a function of the nuclear radius $R$. The solid line shows the result of three-body model calculation, while the dashed line is obtained by switching off the neutron-neutron interaction and assuming the $[(1p_{1/2})^2]$ configuration, respectively.

The size of neutron pair takes a distinct minimum at the peak of two-particle density [9, 10]. Figure 3 shows the local coherence length of the Cooper pair in $^{11}\text{Li}$ as a function of the nuclear radius $R$ obtained with and without the $nn$ interaction. For the uncorrelated calculations, we consider the $[(1p_{1/2})^2]$ configuration and adjust the single-particle potential so that the corresponding single-particle energy is $-0.15$ MeV. One can see that, in the non-interacting
case, the Cooper pair continuously expands, as it gets farther away from the center of the nucleus. In marked contrast, in the interacting case it becomes smaller going from inside to the surface before expanding again into the free space configuration.

3. Dipole excitation
Let us now discuss the dipole excitation of the Borromean nuclei. Recently, the strong low-lying dipole strength distribution has been observed experimentally in the \(^{11}\)Li nucleus [7], which strongly suggests the existence of dineutron correlation in this nucleus. The Coulomb dissociation measurement has also been carried out for the \(^{6}\)He nucleus [11]. Our three-body model calculations well reproduce the experimental data, as shown in Figs. 4 and 5 [12].

One may ask whether a more direct information on the dineutron correlation can be obtained by measuring energy and angular distributions of two emitted neutrons. Notice that the operator which induces the E1 excitation is proportional to the center of mass coordinate of the two valence neutrons, \(\vec{R} = (\vec{r}_1 + \vec{r}_2) / 2\) [2, 13]. Therefore, the relative motion of the two neutrons, \(\vec{r} = \vec{r}_1 - \vec{r}_2\), is not affected by the E1 excitations. It is thus interesting to ask how the energy and angular distributions from the E1 excitation reflect the ground state properties of the Borromean nuclei, especially the correlation for the relative motion of the neutrons, that is, the dineutron correlation.

Figs. 6 and 7 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 [14]. Here, \(e_1\) (\(e_2\)) is the relative energy between the first (second) neutron and the core nucleus. These distributions are obtained using the Green’s function method [13]. 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, only a large ridge at about 0.7 MeV appears, and the strength is largely concentrated around \(e_1 = e_2 = 0.7\) MeV.

In Ref. [14], we have shown that the different behaviours in the strength distribution originate primarily from the property of the neutron-core interaction. The ridge structures reflect the
Figure 6. The dipole strength distribution, \(d^2B(E1)/de_1de_2\), of \(^{11}\text{Li}\) as a function of the energies of the two emitted neutrons relative to the core nucleus. It is plotted in units of \(e^2\text{fm}^2/\text{MeV}^2\).

Figure 7. The dipole strength distribution, \(d^2B(E1)/de_1de_2\), of \(^{6}\text{He}\) as a function of the energies of the two emitted neutrons relative to the core nucleus. It is plotted in units of \(e^2\text{fm}^2/\text{MeV}^2\).

Single-particle resonances, that is, the \(p_{1/2}\) resonance around 0.54 MeV for \(^{10}\text{Li}\) and the \(p_{3/2}\) resonance at 0.91 MeV for \(^{5}\text{He}\). These ridges correspond to the physical process in which one of the neutrons is excited by the dipole field while the other remains near the resonance state as a spectator in the neutron-core system [2, 13]. For \(^{11}\text{Li}\), in addition to the ridge, the dipole strength is concentrated in the region in which one of the neutrons has an energy close to zero. This reflects the \(s\)-wave virtual state in \(^{11}\text{Li}\) close to zero energy.

The correlation measurements for \(^{11}\text{Li}\) have been recently done at RIKEN[15]. We mention that the present calculation shown here is qualitatively in good agreement with the preliminary data.

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