Correlated two-neutron emission in the decay of unbound nucleus $^{26}$O

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The particle unbound $^{26}$O nucleus is located outside the neutron drip line, and spontaneously decays by emitting two neutrons with a relatively long life time due to the centrifugal barrier. We study the decay of this nucleus with a three-body model assuming an inert $^{16}$O core and two valence neutrons. We first point out the importance of the neutron-neutron final state interaction in the observed decay energy spectrum. We also show that the energy and angular distributions for the two emitted neutrons manifest a clear evidence for the strong neutron-neutron correlation in the three-body resonance state. In particular, we find an enhancement of two-neutron emission in back-to-back directions. This is interpreted as a consequence of dineutron correlation, with which the two neutrons are spatially localized before the emission.

Correlations among particles lead to a variety of rich phenomena in many-fermion systems, such as superconductivity and superfluidity. The spatial distribution of particles is also affected by the correlations. For many-electron systems, the Coulomb repulsion between electrons yields the so-called Coulomb hole, in which the distribution of the second electron is largely suppressed in the vicinity of the first electron. In atomic nuclei, in contrast, an attractive nuclear force leads to the dineutron and diproton correlations, with which two nucleons are spatially localized in the surface region of nuclei. These nuclear correlations have attracted lots of attention recently, in connection to physics of weakly bound nuclei.

In order to probe the inter-particle correlation, it has been a standard way in atomic physics to measure a double ionization with strong laser fields. It has been observed that the ionization rate is significantly enhanced due to the electronic correlation, and moreover, there is a strong momentum correlation between the two emitted electrons. The corresponding experiment in nuclear physics is the Coulomb breakup of the Borromean nuclei $^{11}$Li and $^6$He, in which those nuclei are broken up to the core nuclei, $^9$Li and $^4$He, and two neutrons in the Coulomb field of a target nucleus. The observed breakup probabilities, especially those for the $^{11}$Li nucleus, show a sharp peak in the low-energy region, which can be accounted for only by taking into account the neutron-neutron correlations. Furthermore, from the observed strength distribution, the opening angle between the valence neutrons in the ground state of the Borromean nuclei has been inferred employing the cluster sum rule. For both $^{11}$Li and $^6$He, the extracted opening angles were significantly smaller than the value for the independent neutrons, that is, 90 degrees, and clearly indicate the existence of the dineutron correlation.

A small drawback with the cluster sum rule approach is that it yields only an expectation value of the opening angle and a detailed angular distribution cannot be studied with this method. For this reason, the energy and angular distributions of the emitted neutrons from the Coulomb breakup have been investigated. However, it has been concluded that those distributions are largely determined by the properties of the neutron-core system, and thus it is difficult to acquire detailed information on the neutron-neutron correlations from the Coulomb breakup measurement.

It is therefore desirable to seek for other probes for the nucleonic correlation. Among them, the two-proton radioactivity, that is, the spontaneous emission of two protons of proton-unbound nuclei, has been considered to be a good candidate for that purpose. An attractive feature of this phenomenon is that the two valence protons are emitted without an influence of disturbance of nuclei due to an external field. Very recently, the ground state two-neutron emission was discovered for $^{16}$Be. Earlier measurements on the two-neutron emission include those for $^{10}$He and $^{13}$Li. These are a counterpart of the two-proton emission of proton-rich nuclei, corresponding to a penetration of two neutrons over a centrifugal barrier. Subsequently, the two-neutron emission was discovered also for $^{26}$O and $^{13}$Li. So far, the experimental data have been analyzed only with a schematic dineutron model (see also Ref.). Although such schematic model appears to reproduce the data, realistic three-body model calculations with configuration mixings and full neutron-neutron correlations have been clearly urged.

In this paper, we apply the three-body model with a density-dependent contact interaction between the valence neutrons to the decay problem of $^{26}$O, assuming $^{24}$O to be an inert core. This model has been successfully applied to describe the ground state properties and the Coulomb break-up of neutron-rich nuclei. In order to describe the decay of neutron-unbound nucleus, we shall take into account the couplings to continuum by the Green’s function technique, which was invented in Ref., in order to describe the continuum dipole excitations of $^{11}$Li. We shall discuss the role of neutron-
neutron correlation in the decay probability, as well as in the energy and the angular distributions of the emitted neutrons.

In the experiment of Ref. 26, the 26O nucleus was produced in the single proton-knockout reaction from a secondary 27F beam. We therefore first construct the ground state of 27F with a three-body model, assuming the 25F+n+n structure. We then assume a sudden proton removal, that is, the 25F core changes to 24O keeping the configuration for the n+n subsystem of 26O to be the same as in the ground state of 27F. This initial state, \( \Psi_i \), is then evolved with the Hamiltonian for the three-body 24O+n+n system for the two-neutron decay.

We therefore consider two three-body Hamiltonians, one for the initial state 25F+n+n and the other for the final state 24O+n+n. For both the systems, we use similar Hamiltonians as that in Refs. 7, 30,

\[
H = \hat{h}_{NC}(1) + \hat{h}_{NC}(2) + v(1, 2) + \frac{p_1 \cdot p_2}{A_cm},
\]

where \( A_c \) is the mass number of the core nucleus, \( m \) is the nucleon mass, and \( \hat{h}_{NC} \) is the single-particle (s.p.) Hamiltonian for a valence neutron interacting with the core. The last term in Eq. (1) is the two-body part of the recoil kinetic energy of the core nucleus \( \hat{h}_{NC} \), while the one-body part is included in \( \hat{h}_{NC} \). We use a contact interaction between the valence neutrons, \( v \), given as 7, 30,

\[
v(r_1, r_2) = \delta(r_1 - r_2) \left( v_0 + \frac{v_\rho}{1 + \exp((r_1 - R_\rho)/a_\rho)} \right).
\]

Here, the strength \( v_0 \) is determined to be \(-857.2\) MeV.fm\(^3\) from the scattering length for the nn scattering together with the cutoff energy, which we take \( E_{\text{cut}} = 30 \) MeV. See Refs. 7, 30 for the details. The second term in Eq. (2) simulates the density dependence of the interaction. Taking \( R_\rho = 1.34 \times A_c^{1/3} \) fm and \( a_\rho = 0.72 \) fm, we adjust the value of \( v_\rho \) to be 952.3 MeV.fm\(^3\) so as to reproduce the experimental two-neutron separation energy of 27F, \( S_{2n} = 2.80(18) \) MeV 31.

We employ a Woods-Saxon form for the s.p. potential in \( \hat{h}_{NC} \). For the 24O+n+n system, we take \( a = 0.72 \) fm and \( R_0 = 1.25A_c^{1/3} \) fm with \( A_c = 24 \), and determine the values of \( V_0 = -44.1 \) MeV and \( V_{ls} = 45.87 \) MeV.fm\(^2\) in order to reproduce the single-particle energies of \( E_{2s1/2} = -4.09(13) \) MeV and \( E_{1d5/2} = 770^{+20}_{-10} \) keV 32. This potential yields the width for the 1d\(_{5/2}\) state of 92.9 keV, which is compared with the empirical value, \( \Gamma_{1d_{5/2}} = 172(30) \) keV 32. For the 25F+n+n system, one has to modify the Woods-Saxon potential in order to take into account the presence of the valence proton in the core nucleus. The important effect comes from the tensor force between the valence proton and neutrons 33, which primarily modifies the spin-orbit potential in the mean-field approximation 34, 36. We thus use the same Woods-Saxon potential for 25F+n+n system as that for the 24O+n+n system except for the spin-orbit potential, whose strength is weakened to \( V_{ls} = 33.50 \) MeV.fm\(^2\) in order to reproduce the energy of 1d\(_{3/2}\) state in 27F, \( \epsilon_{1d_{3/2}} = -0.811 \) MeV.

With the initial wave function thus obtained, the decay energy spectrum can be computed as 19,

\[
\frac{dP}{dE} = \frac{1}{\pi} \text{Im} \langle \Psi_i | G_0(E) | \Psi_i \rangle - \frac{1}{\pi} \text{Im} \langle \Psi_i | G_0(E) v(1 + G_0(E) v)^{-1} G_0(E) | \Psi_i \rangle \tag{3}
\]

where \( \text{Im} \) denotes the imaginary part. In Eq. (3), \( G_0(E) \) is the unperturbed Green’s function given by,

\[
G_0(E) = \sum_{1,2} \frac{|(j_1j_2^0\eta^+)\rangle \langle (j_1j_2^0\eta^+)|}{e_1 + e_2 - E - i\eta}, \tag{4}
\]

where \( \eta \) is an infinitesimal number and the sum includes all independent two-particle states coupled to the total angular momentum of \( J = 0 \) with the positive parity, described by the three-body Hamiltonian for 24O+n+n. As in our previous study for the continuum E1 excitations of the 11Li nucleus 20, we have neglected the two-body part of the recoil kinetic energy in order to derive Eq. (3), while we keep all the recoil terms in constructing the initial state wave function.

Figure 1 shows the decay energy spectrum obtained with Eq. (3). The solid line shows the correlated spectrum, in which the final state mn interaction is fully taken into account, while the dashed line shows the result without the final state mn interaction. The latter corresponds to the first term in Eq. (3). Since the width of the three-body resonance state is extremely small, which is experimentally the order of \( 10^{-10} \) MeV 37, we have introduced a finite width for a presentation purpose. That is, in evaluating the unperturbed Green’s function, Eq.

\[
\text{FIG. 1: (Color online) The decay energy spectrum for the two-neutron emission decay of 26O. The solid line denotes the result with the full inclusion of the final state neutron-neutron (nn) interaction, while the dashed line shows the result without the final state mn interaction. The theoretical curves are drawn with a finite width of 0.21 MeV, which is the same as the experimental energy resolution. The experimental data, normalized to the unit area, are taken from Ref. 26.}
\]
we set \( \eta = 0.21 \text{ MeV} \), that is to be the same as the experimental energy resolution. Without the final state \( nn \) interaction, the two valence neutrons in \( {}^{26}\text{O} \) occupy the s.p. resonance state of \( 1d_{3/2} \) at 770 keV, and the peak in the decay energy spectrum appears at twice this energy. When the final state \( nn \) interaction is taken into account, the peak is largely shifted towards a lower energy and appears at 0.14 MeV, in a good agreement with the experimental data.

The energy distribution of the two emitted neutrons is shown in Fig. 2, in which a decay amplitude is calculated to a specific two-particle final state [19].

\[
M_{j,l,k_1,k_2} = \langle jj | (1-vG_0-vG_0vG_0-\cdots) | \Psi_i \rangle. \tag{5}
\]

The unperturbed Green’s function, \( G_0 \), is evaluated at \( E = e_1 + e_2 \). Notice that a series of \(-vG_0 + vG_0vG_0-\cdots\) in Eq. (5) describes the multiple rescattering effect of the two neutrons during the emission due to the final state \( nn \) interaction, which is included to the all orders in Eq. (9). In contrast to the case of decay energy spectra shown in Fig. 1, we take \( \eta \) in Eq. (4) to be an infinitesimal number in evaluating the unperturbed Green’s function and use the Gauss-Legendre integration technique for Eq. (9) as described in Ref. [19]. The energy spectrum is then computed as,

\[
\frac{d^2P}{de_1 de_2} = \sum_{j,l} |M_{j,l,k_1,k_2}|^2 \frac{dk_1 dk_2}{de_1 de_2}, \tag{7}
\]

where the factors \( dk/de \) are due to the normalization of the continuum single-particle wave functions, for which we follow Ref. [19].

Figure 2(a) shows the energy distribution obtained by switching off the final state \( nn \) interaction. The energy distribution is dominated by the single-particle \( d_{3/2} \) resonance state at 0.77 MeV. A ridge appears as in the energy distribution for dipole excitations of Borromean nuclei [19, 20]. The energy distribution with the \( nn \) final state interaction is shown in Fig. 2(b). The energy distribution is drastically changed, being highly concentrated along the line of \( e_1 + e_2 \sim 0.14 \text{ MeV} \) with an extremely small width. The variation with \( e_1 \) is weak along this line, although the maximum still appears at \( e_1 = e_2 \). This is a clear manifestation of a three-body resonance, and is in marked contrast to the continuum dipole excitations, in which the final state \( nn \) interaction does not affect much the shape of the energy distribution [20].

The angular distribution obtained without including the final state \( nn \) interaction is shown in Fig. 3. The main component in the initial wave function, \( \Psi_i \), is the \( d_{3/2} \) configuration, and the angular dis-
the box boundary condition as a function of \( r, \theta \) and the opening angle between the two neutrons, \( \theta_{12} \).

The two-particle density for the resonance state of \( ^{26}\text{O} \) obtained with the box boundary condition. It is plotted as a function of \( r_1 = r_2 = r \) and the angle between the valence neutrons, \( \theta_{12} \).

FIG. 4: (Color online) The two-particle density for the resonance state of \( ^{26}\text{O} \) obtained with the box boundary condition. The dot-dashed line in Fig. 3 shows the result obtained by including only \( l \) components. As in the dineutron correlation in the density distribution [4], the angular distribution clearly prefers the emission of two neutrons in the back-to-back angles. The nuclear phase shifts, \( \delta_1 + \delta_2 \), play a minor role in the decay of \( ^{26}\text{O} \). partly because the decay energy is extremely small. Evidently, the back-to-back emission of two neutrons in the momentum space from the decay of \( ^{26}\text{O} \) is another manifestation of the strong dineutron correlation in the coordinate space of ground state density distribution.

For \( ^{16}\text{Be} \) and \( ^{11}\text{Li} \), the experimental angular distributions show an enhancement of emission with relatively small opening angles [25, 28]. It has yet to be clarified why these nuclei show different angular distributions from \( ^{26}\text{O} \) (and from \( ^{4}\text{Be} \) and \( ^{11}\text{Li} \)). One possible reason is that the nuclear phase shift might play a more important role in these nuclei so that the phase factor \( e^{-i\delta} \) is canceled out. Another reason may be the core excitation, with which the \( nn \) configuration with coupled angular momenta of \( J \neq 0 \) is largely admixed in the ground state wave function. In order to confirm these points, three-body model calculations for these nuclei with the core excitations are clearly needed, but we leave them as a future work.

In summary, we have used the three-body model with a contact neutron-neutron interaction in order to analyze the two-neutron emission decay of the unbound neutron-rich nucleus \( ^{26}\text{O} \). Using the Green’s function technique, we have analyzed the decay energy spectrum, the energy and the angular distributions of the two emitted neutrons. We have pointed out that the final state \( n-n \) interaction plays a crucial role to reproduce the strong low energy peak of the experimental decay energy spectrum. We have also argued that the energy distribution is a clear manifestation of a three-body resonance state and its density distribution is strongly reflected in the angular distribution of the emitted neutrons. In particular, the angular distribution clearly prefers the emission of the two neutrons in the back-to-back angles, that can be interpreted as a clear evidence for the dineutron correlation. So far, the energy and the angular distributions for the two-neutron decay of \( ^{26}\text{O} \) have not yet been measured experimentally. It would be extremely intriguing if they will be measured at new generation RI beam facilities, such as the SAMURAI facility at RIBF at RIKEN [41].

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