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Three-body Description of 2*n*-Halo and Unbound 2*n*-Systems: ^{22}C and ^{26}O

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We study the two-neutron correlations in the ground state of the weakly-bound two-neutron halo nucleus ^{22}C sitting at the edge of the neutron-drip line and also in the unbound nucleus ^{26}O sitting beyond the neutron dripline. For the present study, we employ a three-body (core + n + n) structure model designed for describing the two-neutron halo system by explicit inclusion of unbound continuum states of the subsystem (core + n). We use either a density-independent or a density-dependent contact-delta interaction to describe the neutron-neutron interaction and its strength is varied to fix the binding energy. We report the configuration mixing in the ground state of these systems for different choices of pairing interactions.

KEYWORDS: Two-neutron halo, Two-neutron unbound system, Two-neutron correlations.

1. Introduction

The new generation of radioactive ion beam facilities around the various parts of the globe has provided the access to the neutron-rich side of the nuclear chart. Due to this, there has been a rapidly increasing interest in the physics of the two-neutron (2n) halo nuclei sitting right on the top of neutron driplines and decays of 2n-unbound systems beyond the neutron dripline. These systems demand a three-body (3b) description with proper treatment of continuum, the conventional shell-model assumptions being insufficient. The well established 2n-halo ^{6}He has long history of studies in 3b-framework and thus it can be safely remarked that the understanding of 3b-dynamics is fairly established for p-shell nuclei, whereas for the s-d shell nuclei still the situation is in progress stage [1]. In the present study we consider two different s-d shell nuclei, the 2n-halo ^{22}C and the 2n-unbound system ^{26}O. Very recently a high precision measurement of the interaction cross-section for ^{22}C was made on a carbon target at 235 MeV/nucleon [2] and also the unbound nucleus ^{26}O has been investigated, using invariant-mass spectroscopy [3] at RIKEN. The structural spectroscopy of the two-body subsystem plays a vital role in the understanding the 3b-system. These high precision measurements and the sensitivity of the structural spectroscopy of subsystem with the structure of 3b-system (core+n + n), are the motivation for selecting these nuclei for the present study. We have studied the pairing collectivity in the ground state of the 2n-halo ^{22}C and in the the 2n-unbound system ^{26}O. For this study we have used our recently implemented 3b-structure model (core+n + n) for the ground and continuum states of the 2n-halo nuclei [4–6]. We have explored the role of different pairing interactions such as density independent (DI) contact-delta pairing interaction and density dependent (DD) contact-delta pairing interaction with the configuration mixing in the ground-state of these systems.

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2. Model Formulation

In our approach we consider a 3b-system consisting of an inert core nucleus and two valence neutrons, which is specified by Hamiltonian

$$H = -\frac{\hbar^2}{2\mu}\sum_{i=1}^{2}\nabla_i^2 + \sum_{i=1}^{2} V_{\text{core}+n}(\vec{r}_i) + V_{12}(\vec{r}_1, \vec{r}_2) \tag{1}$$

where $\mu = A_c m_N/(A_c + 1)$ is the reduced mass, and m_N and A_c are the nucleon mass and mass number of the core nucleus, respectively. The recoil term is neglected in the present study, as $A_c = 20$ and 24 are large enough to ignore it. $V_{\text{core}+n}$ is the core-n potential and V_{12} is n-n potential. The neutron single-particle unbound s-, p-, d- and f-wave continuum states of the subsystem ^{21}C and and ^{25}O are calculated in a simple shell model picture for the converged model parameter, bin width ($\Delta E = 0.1$), by using the Dirac delta normalization and are checked with a more refined phase-shift analysis. These core + n continuum wave functions are used to construct the two-particle states of the core + n + n system by proper angular momentum couplings. We use a density-independent (DI) contact-delta pairing interaction for simplicity, and its strength is the parameter which will be fixed to reproduce the ground-state energy. We have also used a density-dependent (DD) contact-delta pairing interaction. For a detailed formulation one can refer to [4–6].

3. Two-body unbound subsystems (core + *n*)

The investigation of the two-body (core + n) subsystem is crucial in understanding the three-body system (core + n + n). The interaction of the core with the valence neutron (n) plays a vital role in the binding mechanism of the core + n + n system. The elementary concern over the choice of a core + n potential is the scarce experimental information about the core-neutron systems. We employ the following core + n potential

$$V_{\text{core}+n} = \left(V_0^l + V_{ls}\vec{l}\cdot\vec{s}\frac{1}{r}\frac{d}{dr}\right)\frac{1}{1+\exp\left(\frac{r-R_c}{a}\right)}, \tag{2}$$

where $R_c = r_0 A_c^{\frac{1}{3}}$ with r_0 and a are the radius and diffuseness parameter of the Woods-Saxon potential.

3.1 ^{21}C

For ^{21}C, not much is known beyond that it is unbound. The only available experimental study using the single-proton removal reaction reported the limit to the scattering length $|a_0|< 2.8$ fm and due to the low statistics of this experimental data at low energies, the possibility of low-lying resonance states can not be ruled out [7]. In the view of exploring the sensitivity of the core-n potential to the possible resonances and configuration mixing in the ground state of ^{22}C, very recently we examined in detail the four different potential sets (for details see text and Table 1 of Ref. [6]). Here we will discuss the results corresponding to potential Set-1, which is adopted from the literature [9], beacuse of its acceptance by different 3-body models leading to good explanation of the observed properties for ^{22}C. The subshell closure of the neutron number 14 is assumed for the core configuration given by $(0s_{1/2})^2(0p_{3/2})^4(0p_{1/2})^2(0d_{5/2})^6$. The seven valence neutron continuum orbits, i.e., $s_{1/2}$, $d_{3/2}$, $f_{7/2}$, $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ and $d_{5/2}$ are considered in the present calculations for ^{21}C.

3.2 ^{25}O

In the recent measurement conducted at RIKEN [3], along with high accuracy measurement of ground state of ^{26}O, they have also reported the $d_{3/2}$ resonance state at 749(10) keV with width of 88(6) keV for ^{25}O. This information will serve as input for fixing the core+n potential parameters. For ^{25}O, we adopt the same value for the diffuseness parameter (a) and the radius parameter (r_0), as in Ref. [10]. For the Wood-Saxon depth parameter (V_0) and the strength of spin-orbit potential (V_{ls}) parameter tabulated in Table I, we use the information for the energy of unbound $d_{3/2}$ state. Our parameters for V_0 and V_{ls} are consistent with the one reported in Ref. [10]. The neutron number 16 is assumed for the core configuration given by $(0s_{1/2})^2(0p_{3/2})^4(0p_{1/2})^2(0d_{5/2})^6(1s_{1/2})^2$. The three

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Table I. Parameter sets of the core-n potential for $l = 1, 2, 3$ states of a ^{24}O+n system. The possible resonances with resonance energy E_R and decay width Γ in MeV are also tabulated.

lj	r_0(fm)	a(fm)	V_0(MeV)	V_{ls}(MeV)	E_R(MeV)	Γ(MeV)
$d_{3/2}$			-44.10	22.84	0.740	0.086
$p_{3/2}$	1.25	0.72	-48.67	22.84	0.570	1.382
$f_{7/2}$			-44.10	22.84	2.440	0.206

valence neutron continuum orbits, i.e., $d_{3/2}$, $p_{3/2}$ and $f_{7/2}$ are considered in the present calculations for ^{25}O.

4. Results and Discussions

The 3b-model with two non-interacting particles in the above single-particle levels of ^{21}C and ^{25}O produces different parity states, when two neutrons are placed in different unbound orbits. The seven configurations, $(s_{1/2})^2$, $(p_{1/2})^2$, $(p_{3/2})^2$, $(d_{3/2})^2$, $(d_{5/2})^2$, $(f_{5/2})^2$ and $(f_{7/2})^2$ couple to $J^\pi = 0^+$ for ^{22}C and three configurations $(d_{3/2})^2$, $(p_{3/2})^2$ and $(f_{7/2})^2$ couple to $J^\pi = 0^+$ for ^{26}O. In the 3b-calculations, along with the core-n potential the other important ingredient is the n-n interaction. An attractive contact-delta pairing interaction is used, $g\delta(\vec{r}_1 - \vec{r}_2)$ for simplicity, with the only adjustable parameter being g. We also use the DD contact-delta pairing interaction to explore the role of different pairing interactions. In the DD contact-delta pairing interaction (defined by Eq. (8) of Ref. [6]), the strength of the DI part is given as $v_0 = 2\pi^2 \frac{\hbar^2}{m_N} \frac{2a_{nn}}{\pi - 2k_c a_{nn}}$, where a_{nn} is the scattering length for the free neutron-neutron scattering and k_c is related to the cutoff energy, e_c, as $k_c = \sqrt{\frac{m_N e_c}{\hbar^2}}$. We use $a_{nn} = 15\,\text{fm}$ and $e_c = 30\,\text{MeV}$ [10], which leads to $v_0 = 857.2\,\text{MeV fm}^3$. For the parameters of the DD part, we determine them so as to fix the ground-state energy of ^{22}C and ^{26}O, $E = -0.140$ MeV [8] and 0.018 MeV [3] respectively. The values of the parameters that we employ are $R_\rho = 1.25 \times A_c^{\frac{1}{3}}$ ($A_c = 20, 24$), $a = 0.65$ fm. and $v_\rho = 591.55$ and $1058.70\,\text{MeV fm}^3$ for ^{22}C and ^{26}O respectively. We found that configuration mixing in the ground state of ^{22}C does not change much with the choice of $n - n$ interaction. We present the numbers for our potential Set 1 in Table II which are consistent with results of Ref. [9], and the same behavior is observed for the other sets [6]. Whereas for the ^{26}O case our results report different magnitude of configuration mixing for the different interactions and the results corresponding to the DD part that are consistent with the results of Ref. [10], where they have also used the DD interaction. One possible reason for this difference is that ^{26}O is unbound by 18 keV whereas ^{22}C is bound by 0.140 MeV. In order to reach a final conclusion we need more analysis, which will be reported elsewhere. The two particle density of ^{22}C and ^{26}O as a function of two radial coordinates, r_1 and r_2, for valence neutrons, and the angle between them, θ_{12} in the LS-coupling scheme is calculated by following Refs. [5, 10]. The distribution at smaller and larger θ_{12} are referred to as “di-neutron”and “cigar-like”configurations, respectively. One can see in Fig. 1 that the two-particle density is well concentrated around $\theta_{12} \leq 90°$, which is the clear indication of the di-neutron correlation and the di-neutron component has a relatively higher density in comparison to the small cigar-like component for both ^{22}C and ^{26}O. The reflection of dominance of s-component in ground state of ^{22}C can be seen in left panel of Fig. 1 showing extended di-neutron component in comparison to ^{26}O (in right panel of Fig. 1), which has sharper dineutron component due to the mixing of $l > 0$ components in its ground-state.

5. Conclusions

In the present study we present the emergence of bound $2n$-halo ground state of ^{22}C from the coupling of seven unbound $spdf$-waves in the continuum of ^{21}C and $2n$-unbound ground state of ^{26}O from the coupling of three unbound pdf-waves in the continuum of ^{25}O due to presence of

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Table II. Components of the ground state (0^+) of ^{22}C and ^{26}O, with model parameter energy cut E_{cut}. For ^{22}C we have used the potential Set 1 of Table 1 of [6] for the shallow case with the ground-state energy, −0.140 MeV and for ^{26}O we have used the potential tabulated in Table I. In last column of the table, the comparison has been made with the Ref. [9] for ^{22}C and Ref. [10] for ^{26}O.

System	E_{cut} (MeV)	lj	DI	DD	Reference
			Present work		
^{22}C	5	$(s_{1/2})^2$	0.923	0.899	0.915
		$(p_{1/2})^2$	0.004	0.008	0.009
		$(p_{3/2})^2$	0.022	0.029	0.024
		$(d_{3/2})^2$	0.045	0.047	0.033
		$(d_{5/2})^2$	0.001	0.005	0.003
		$(f_{5/2})^2$	0.0003	0.001	0.033
		$(f_{7/2})^2$	0.003	0.007	0.007
^{26}O	10	$(d_{3/2})^2$	0.798	0.643	0.661
		$(p_{3/2})^2$	0.024	0.088	0.105
		$(f_{7/2})^2$	0.178	0.268	0.183

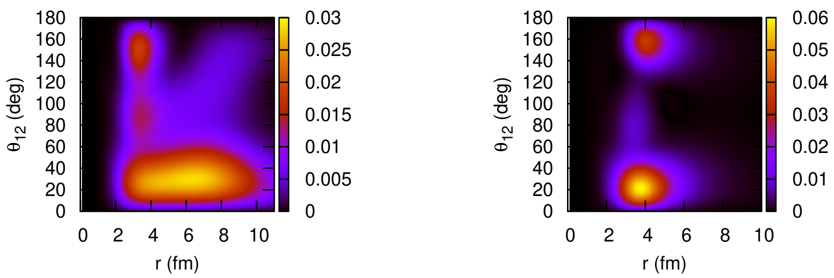

Fig. 1. Two-particle density for the ground state of ^{22}C (left-panel) and ^{26}O (right-panel) as a function $r_1 = r_2 = r$ and the opening angle between the valence neutrons θ_{12} for settings mentioned in caption of Table II .

pairing interaction. Contribution of different configurations has been presented along with the $2n$-correlations. More investigations are needed to comment on the role of different pairing interactions and to explain in detail the role of each wavefunction component.

References

[1] S. N. Ershov and B. V. Danilin, Phys. Part. Nucl. **39**, 835 (2008).
[2] Y. Togano et al., Phys. Lett. **B761**, 412-418 (2016).
[3] Y. Kondo et al., Phys. Rev. Lett. **116**, 102503 (2016).
[4] L. Fortunato, R. Chatterjee, Jagjit Singh and A. Vitturi, Phys. Rev. C **90**, 064301 (2014).
[5] Jagjit Singh, L. Fortunato, A. Vitturi and R. Chatterjee, Eur. Phys. J. A **52** 209 (2016).
[6] Jagjit Singh, W.Horiuchi, L. Fortunato and A.Vitturi, Few-Body Syst **60**:50 (2019).
[7] S. Mosby *et al.*, Nucl. Phys. A **909**, 69 (2013).
[8] L. Gaudefroy *et al.*, Phys. Rev. Lett. **109**, 202503 (2012).
[9] W. Horiuchi and Y. Suzuki, Phys. Rev. C **74**, 034311 (2006).
[10] K. Hagino and H. Sagawa, Phys. Rev. C **93**, 034330 (2016).

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