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Sensitivity of core+n potential on configuration mixing in ground state of neutron-rich exotic nuclei

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Abstract. We study the configuration mixing in the ground state of the neutron-rich exotic nuclei. The results for weakly-bound two-neutron halo nuclei ^{11}Li and ^{22}C, and the two-neutron unbound nucleus ^{26}O are reported. For the present study, we use a three-body (core + n + n) structure model developed for describing the two-neutron halo system by explicit coupling of unbound continuum states of the subsystem (core + n). We use 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 two-neutron correlations in the ground state of these systems.

1. Introduction

Since the discovery of neutron halos [1], astounding advancements have been made in technology of radioactive ion beam (RIB) facilities. These upgrades in RIB facilities has provided the access to the neutron-rich sea of the nuclear chart. Due to this, the neutron-rich side of the nuclear chart has gained extensive attention of the nuclear physics community, particularly the two-neutron ($2n$) halo nuclei sitting right on the top of neutron driplines and decays of $2n$-unbound systems beyond the neutron dripline, consisting of a core and two valence neutrons. The structure of these systems is very much different from well known stable systems lying in the stability valley, due to which these systems demand a genuine three-body (3b) description with proper treatment of continuum. The stability of such 3b-system (core+$n+n$) is linked to the continuum spectrum of the two-body (core+n) subsystem. In this context, to explore the sensitivity of choice of a core+n potential with the configuration mixing in the ground state of 3b-systems (core+$n+n$), we will discuss the results of the $2n$-halos ^{11}Li, ^{22}C and $2n$-unbound system ^{26}O.

Recently all these systems have been experimentally investigated at TRIUMF and RIKEN, the major experimental facilities of Canada and Japan, respectively. Although ^{11}Li is the first observed two-neutron halo four decades ago [1]. Since then a lot of experimental and theoretical studies have been reported on the structure of the ^{11}Li. Recently the role of ^{10}Li resonances is investigated in the halo structure of ^{11}Li via ^{11}Li$(p,d)^{10}$Li transfer reaction at TRIUMF [3] and at the same facility the first conclusive evidence of a dipole resonance in ^{11}Li having an isoscalar character has been reported [5, 6]. Also for ^{22}C a high precision measurement of the interaction cross-section was made on a carbon target at 235 MeV/nucleon [7] and ^{26}O has been investigated, using the invariant-mass spectroscopy [8] at RIKEN. The structural spectroscopy of the two-body subsystem plays a vital role in the understanding of 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.

Very recently, we have studied in detail the pairing collectivity in the ground state of the $2n$-halo ^{22}C [9, 10] and in the the $2n$-unbound system ^{26}O [10]. Here we will discuss the results for these two systems along with our new results on ^{11}Li. 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 [9, 11, 12]. We have reported the configuration mixing in the ground-state of these systems with a particular choice of core+n potential depending upon available experimental information.

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 the 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. $V_{\text{core}+n}$ 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 ^{10}Li, ^{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-dependent (DD) contact-delta pairing interaction [19], given by

$$V_{12} = \delta(\vec{r}_1 - \vec{r}_2)\left(v_0 + \frac{v_\rho}{1+\exp[(r_1 - R_\rho)/a_\rho]}\right). \tag{2}$$

The first term in Eq. (2) with v_0 simulates the free n-n interaction, which is characterized by its strength and the second term in Eq. (2) represents density-dependent part of the interaction. The strengths v_0 and v_ρ are scaled with the ΔE by following relation from Ref. [9]. The v_ρ is the parameter which will be fixed to reproduce the ground-state energy. For a detailed formulation one can refer to [9, 11, 12].

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

$$V_{\text{core}+n} = \left(V_0^l + V_{ls}\vec{l}\cdot\vec{s}\frac{1}{r}\frac{d}{dr}\right)\frac{1}{1+\exp\left(\frac{r-R_c}{a}\right)}, \tag{3}$$

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.

Table 1. Parameter sets of the core-n potential for different j states of ^{9}Li+n, ^{20}C+n and ^{24}O+n. The possible resonances with resonance energy E_R and decay width Γ in MeV are also tabulated.

System	lj	r_0(fm)	a(fm)	V_0(MeV)	V_{ls}(MeV)	E_R(MeV)	Γ(MeV)
	$s_{1/2}$			−47.50	–	–	–
^{10}Li	$p_{1/2}$	1.27	0.67	−40.00	21.02	0.46	0.36
	$d_{5/2}$			−47.50	21.02	2.98	1.39
	$s_{1/2}$			−33.00	–	–	–
^{21}C	$d_{3/2}$	1.25	0.65	−47.50	35.00	0.92	0.09
	$f_{7/2}$			−42.00	35.00	6.69	2.93
	$d_{3/2}$			−44.10	22.84	0.74	0.09
^{25}O	$p_{3/2}$	1.25	0.72	−48.67	22.84	0.57	1.38
	$f_{7/2}$			−44.10	22.84	2.44	0.21

3.1. ^{10}Li
For ^{10}Li ($N = 7$ and $Z = 3$), we use a potential set consistent with the P4 model of Ref. [13] and this potential reproduces the observed $p_{1/2}$ resonance at 0.45 MeV [3, 4] and $d_{5/2}$ resonance, which lies at higher energy around 2.98 MeV, this position is consistent with high-lying structure of ^{10}Li reported in [4]. For present calculations we have ignored the spin of the core ^{9}Li. The neutron number 6 is assumed for the core configuration given by $(0s_{1/2})^2(0p_{3/2})^4$. The four valence neutron continuum orbits, i.e., $p_{1/2}$, $d_{5/2}$, $s_{1/2}$ and $d_{3/2}$ are considered in the present calculations for ^{10}Li. The parameter set used in the present study is tabulated in Table 1.

3.2. ^{21}C
For ^{21}C ($N = 15$ and $Z = 6$), not much information 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 [14]. 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. [9]). In the present manuscript the results corresponding to potential set tabulated in Table 1 will be discussed. 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.

3.3. ^{25}O
In the recent measurement conducted at RIKEN [8], along with high accuracy measurement of the 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 ($N = 17$ and $Z = 8$), we adopt the potential set from our recent study reported in Ref. [10]. For the Wood-Saxon depth parameter (V_0) and the strength of spin-orbit potential (V_{ls}) parameter tabulated in Table 1, we use the information for the energy of unbound $d_{3/2}$ state. Our parameter set is consistent with the one reported in Ref. [19]. 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 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 ^{10}Li, ^{21}C and ^{25}O produces different parity states, when two neutrons are placed in different unbound orbits. The four configurations $(s_{1/2})^2$, $(p_{1/2})^2$,$(d_{3/2})^2$, $(d_{5/2})^2$ couple to $J^\pi = 0^+$ for ^{11}Li, 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. We use the DD contact-delta pairing interaction, with the only adjustable parameter being v_ρ. In the DD contact-delta pairing interaction (defined by Eq. (2)), 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 $e_c = 30\,\text{MeV}$ [19], 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 ^{11}Li, ^{22}C and ^{26}O, $E = -0.370$ MeV [15], $E = -0.140$ MeV [16] and 0.018 MeV [8] respectively. The values of the parameters that we employ are $R_\rho = 1.25 \times A_c^{\frac{1}{3}}$ ($A_c = 9, 20, 24$) and $v_\rho = 861.75, 591.55$ and $1058.70\,\text{MeV fm}^3$ for ^{11}Li, ^{22}C and ^{26}O respectively.

We report the percentage configuration mixing in the ground state of these three systems in Table 2. We found for this particular choice of core+n potential, ^{11}Li is p-neutron halo, ^{22}C is s-neutron halo and where as for ^{26}O case our results report mixed configuration mixing without any particular angular momentum dominance. These results of configuration mixing are consistent with the results of Ref. [13] for ^{11}Li, of Ref. [17, 18] for ^{22}C and of Ref. [19] for ^{26}O. The detailed results of configuration mixing with different choices of pairing interaction for ^{22}C and ^{26}O are reported in Ref. [9, 10]. The detailed investigation of configuration mixing for different choices of pairing interactions and core+n potential for ^{11}Li are in progress, very soon will be reported elsewhere.

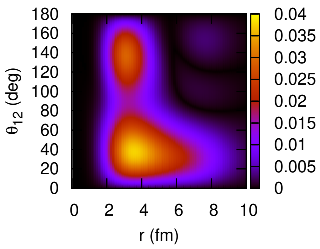
The two particle density of ^{11}Li, ^{22}C and ^{26}O as a function of two radial coordinates, r_1 and r_2, for valence neutrons, and the angle between them, θ_{12} in the LS-coupling scheme is calculated by following Refs. [12, 19]. The distribution at smaller and larger θ_{12} are referred to as "di-neutron"and "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 all three cases i.e. ^{11}Li, ^{22}C and ^{26}O. The reflection of dominance of p-component and s-component in ground state of ^{11}Li and ^{22}C can be seen in of Fig. 1(a) and Fig. 1(b) showing extended di-neutron component in comparison to ^{26}O (in panel (c) of Fig. 1), which has shrunk di-neutron component due to the mixing of $l > 0$ components in its ground-state.

5. Summary

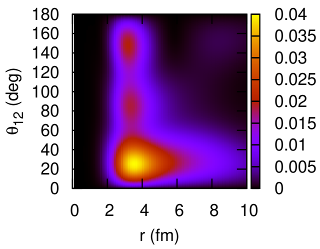
In the present study we report the emergence of bound $2n$-halo ground state of ^{11}Li and ^{22}C from the coupling of four unbound *spd*-waves and seven unbound *spdf*-waves in the continuum of ^{10}Li and ^{21}C respectively due to the presence of pairing interaction. Also the emergence of $2n$-unbound ground state of ^{26}O from the coupling of three unbound *pdf*-waves in the continuum of ^{25}O due to the presence of the pairing interaction is reported. The configuration mixing in the ground state of these neutron-rich nuclei has been reported for a particular choice of core+n potential fixed in the view of the available recent experimental data. Also two-neutron correlation for these systems showing dominance of di-neutron component is discussed. Investigation with different choices of pairing interactions and core+n potential for ^{11}Li are in progress and will be reported elsewhere.

Table 2. Components of the ground state (0^+) of ^{11}Li, ^{22}C and ^{26}O, with the model parameter energy cut E_{cut}. For ^{11}Li, ^{22}C and ^{26}O the core+n potential tabulated in Table 1 are used. In the last column of the table, the comparison has been made with Ref. [13] for ^{11}Li, Ref. [17] for ^{22}C and Ref. [19] for ^{26}O.

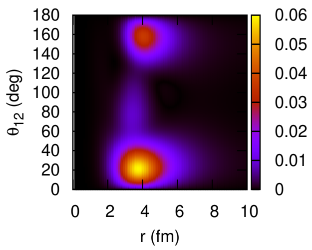
System	E_{cut} (MeV)	lj	Present work	Reference
^{11}Li	5	$(s_{1/2})^2$	0.245	0.270
		$(p_{1/2})^2$	0.596	0.670
		$(d_{5/2})^2$	0.091	0.030
		$(d_{3/2})^2$	0.012	–
^{22}C	5	$(s_{1/2})^2$	0.819	0.823
		$(p_{1/2})^2$	0.006	–
		$(p_{3/2})^2$	0.035	0.010
		$(d_{3/2})^2$	0.084	0.158
		$(d_{5/2})^2$	0.003	–
		$(f_{5/2})^2$	0.0001	–
		$(f_{7/2})^2$	0.0049	0.007
^{26}O	10	$(d_{3/2})^2$	0.643	0.661
		$(p_{3/2})^2$	0.088	0.105
		$(f_{7/2})^2$	0.268	0.183



(a) ^{11}Li



(b) ^{22}C



(c) ^{26}O

Figure 1. Two-particle densities for the ground state of ^{11}Li, ^{22}C and ^{26}O 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 2.

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