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Core momentum distribution in two-neutron halo nuclei

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ABSTRACT

The core momentum distribution of a weakly-bound neutron–neutron–core exotic nucleus is computed within a renormalized zero-range three-body model, with interactions in the s-wave channel. The halo wave-function in momentum space is obtained by using as inputs the two-body scattering lengths and the two-neutron separation energy. The core momentum densities are computed for ^{11}Li, ^{14}Be ^{20}C and ^{22}C. The model describes the experimental data for ^{11}Li, ^{14}Be and to some extent ^{20}C. The recoil momentum distribution of the ^{20}C from the breakup of ^{22}C nucleus is computed for different two-neutron separation energies, and from the comparison with recent experimental data the two-neutron separation energy is estimated in the range $100 \lesssim S_{2n} \lesssim 400$ keV. The recoil momentum distribution depends weakly on the neutron-^{20}C scattering length, while the matter radius is strongly sensitive to it. The expected universality of the momentum distribution width is verified by also considering excited states for the system.

1. Introduction

The core recoil momentum distribution of radioactive two-neutron halo nuclei close to the drip line, extracted from breakup reactions at few hundreds MeV/A, are expected to be quite useful in order to get insights on the underlying neutron–neutron–core structure of these exotic nuclei [1,2]. This is particularly clear in the example of ^{11}Li breakup in a carbon target at 800 MeV/A [1], where the momentum distribution is characterized by the sum of two distributions, a narrow one with $\sigma = 21(3)$ MeV/c and a wide one with $\sigma = 80$ MeV/c, given that σ^2 is the variance associated with a normal distribution. The narrow momentum distribution should be associated with a large configuration of the two neutrons forming a halo structure. In this case the breakup occurs when the two neutrons are found quite far from the core, corresponding to a weakly-bound three-body system in the nuclear scale. On the other hand, the wide momentum distribution is related to the inner part of the halo neutron orbits, close to the core region.

An interesting aspect of two-neutron halo states, associated with the narrow core momentum distribution, is that the halo constituents should have a high probability to be found in the classically forbidden region, outside the potential range. Therefore, the halo wave function should be quite insensitive to details of the interactions, once the model is adjusted by the best known two- and three-body low-energy observables. Therefore, one natural observable is the two-neutron separation energy, S_{2n}, which represents the three-body binding. For the two-body subsystems neutron–neutron (n–n) and neutron–core (n–c), the appropriate observables are the corresponding scattering lengths (or, respective, two-body energies). With these arguments, studies with schematic potentials, such as contact interactions, have been quite successful in describing low-energy three-body structures for large two-body scattering lengths (when the corresponding energies are close to zero). Actually, investigations on quantum three-body systems within this regime, in nuclear and atomic physics, became quite well known in view of recent experimental realizations in atomic laboratories of the long-time predicted Efimov effect [3], which corresponds to the increasing number of excited three-body states as one goes to the unitary limit (when one or both two-body scattering lengths are close to infinity). For some reports, quoting the main experimental realizations of this effect, see Refs. [4–6].

By considering a contact interaction, the corresponding wave-function is an eigenstate of the free Hamiltonian, except in the positions where the particles are right on the top of each other; and, therefore, the particles are in the classically forbidden region

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(see, e.g., [7]). Such theoretical approach applied to light-exotic nuclei close to the neutron drip-line, within a neutron–neutron–core (n–n–c) configuration, is described in detail in a recent review, in Ref. [8], where universal aspects of the properties of the weakly-bound n–n–c systems are emphasized.

Our focus here is to present a theoretical investigation concerned to the experimental core recoil momentum distributions of the halo-nuclei ^{11}Li [1], ^{14}Be [9], ^{20}C and ^{22}C [10], as obtained by the halo breakup on nuclear targets (see also Ref. [11]). The approach is the above described three-body model, which we found appropriate for the analysis of low-binding energy systems as these ones. In the particular cases of ^{11}Li, ^{14}Be and the carbon systems ^{20}C and ^{22}C, we consider that the neutron–neutron and the neutron–core interactions are dominated by s-wave states. The calculations of core momentum distributions are performed within a renormalized zero-range three-body model, with the halo nucleus described as two neutrons with an inert core (n–n–c) [8,12]. The detailed expressions for the momentum distribution are given in [13], within an approach that requires as inputs one two-body (n–c) and one three-body (n–n–c) observable, given that the other two-body observable is fixed to the well-known virtual-state energy of the n–n system. Usually, within such approach it is appropriate to consider the corresponding two-body scattering lengths (positive, for bound, and negative for virtual state systems); with a three-body scale given by the two-neutron separation energy, S_{2n}. Therefore, in a more general description of low-energy three-body physics with two distinguished particles (α–α–β), an appropriate universal scaling function is given (see e.g. [8]), where only three low-energy inputs are enough to determine any other relevant low-energy observable of the system.

Within our study on the momentum distributions of the core in halo nuclei the observable that we are concerned is the variance of the momentum distribution, given by σ^2 (associated with the normal one), which is universally correlated to the two possible scattering lengths and S_{2n}. One obtains σ from the Full Width at Half Maximum (FWHM) of the momentum distribution, such that one can find that FWHM $= 2\sqrt{2\ln 2}\,\sigma$. Once this quantity is known experimentally, one can use the scaling function to estimate the value of S_{2n} or, eventually, to constraint some other poorly known low-energy observable, such as a subsystem energy, or scattering length. The natural units for σ in halo physics is MeV/c. As we are interested in scaling properties of observables, it is convenient to introduce the dimensionless ratio $\sigma/\sqrt{S_{2n}m_n}$, where m_n is the nucleon mass. By taking m_n as the mass unit, a scaling function can be defined, with a general form given by

$$\frac{\sigma}{\sqrt{S_{2n}}} = \mathcal{S}_c\left(\pm\sqrt{\frac{E_{nn}}{S_{2n}}}, \pm\sqrt{\frac{E_{nc}}{S_{2n}}}; A\right), \tag{1}$$

where the $+$ and $-$ signs refer to the bound and virtual subsystem energies, respectively. The core mass number is $A \equiv m_c/m_n$. The corresponding energies, E_{nn} and E_{nc}, are positive defined quantities, with a_{nn} and a_{nc} being the respective two-body scattering lengths. In our specific case of the two-neutron halo nuclei the above scaling function (1) has E_{nn} fixed to the n–n virtual state. In the next, our units are such that the Planck constant $\hbar$ and the velocity of light c are set to one. All masses are taken in units of m_n.

The definition of the scaling function (1) follows the same approach that was previously considered in Ref. [14], when studying universal aspects of Efimov states for light halo nuclei with renormalized zero range interactions. In Refs. [15,16], within the renormalization of the three-body problem with short-range interactions, it was discussed how the concept of a limit cycle applies for large two-body scattering lengths, in close relation to the Efimov effect. The correlation function (1), computed close to the unitary limit, is valid for all the tower of geometrically spaced Efimov states, which are related by the factor $\mathrm{e}^{-2\pi/s_0^A}$, where s_0^A depends on the mass ratio A [13]. Therefore, close to this limit, when the two-body energies are scaled by this geometrical factor, all the properties of the halo state are rescaled, like the value of the momentum distribution, which changes as $\sigma \to \mathrm{e}^{-\pi/s_0^A}\sigma$ at each cycle. This geometrical factor is whipped out in $\sigma/\sqrt{S_{2n}}$, with this function replicating in itself at each Efimov cycle. This will be exemplified in our results.

For the momentum distribution width, the scaling function (1) is the limit cycle of the correlation function associated with σ as a function of E_{nn}, E_{nc} and S_{2n}, when the three-body ultraviolet (UV) cut-off is driven to infinite in the three-body integral equations; or, correspondingly, when the scattering lengths are driven to zero with a fixed UV cut-off. Within a renormalized zero-range three-body model, similar procedure is performed in the subtracted integral equations, where the subtraction energy scale is fixed and the two-body scattering lengths are driven towards infinite. In practice, both procedures provides very close results, as shown in Ref. [17]. In the exact Efimov limit ($E_{nn} = E_{nc} = 0$), the width is a universal function of the mass number A, $\sigma/\sqrt{S_{2n}} = \mathcal{S}_c\,(0, 0, A)$, which is associated to a limit cycle. Already in the first cycle it approaches the results of the renormalized zero-range three-body model (see e.g. [8]), namely given by the subtracted Skorniakov and Ter-Martirosian equations for mass imbalanced systems [18].

For the analysis of the core momentum distribution, we consider data for ^{11}Li [1], ^{14}Be [9] and ^{20}C [10] as the low-energy parameters, which are the inputs of our renormalized zero-range model. This procedure allows us to verify the utility of such "bare" formula (1), which does not include distortion effects from the scattering, to analyze the actual breakup data for those systems, taken at few-hundred MeV/A.

As an application of our model, we study in more detail the two-neutron halo of ^{22}C, an exotic nucleus which was first observed in 1986, as reported in Ref. [19]. Within a three-body n–n-^{20}C configuration, this is a Borromean nucleus, as it was already known that ^{21}C is unstable [20]. Our attempt is to extract information of the halo properties, by using the correlation between observables expressed in Eq. (1), namely the width of the core recoil distribution as a function of S_{2n} and the energy of the s-wave virtual state of ^{21}C. This halo-nucleus was previously suggested in Ref. [21], within a study on the possible occurrence of Efimov states. Later on, in Ref. [22], by studying structure and reactions of halo nuclei, it was also considered as a possible Borromean system. This particular case is of interest considering that the corresponding observables are probably dominated by the tail of the three-body wave function in an ideal s-wave three-body model, as suggested in Ref. [23].

From the experimental point of view, the two-neutron separation energy of ^{22}C is not well constrained, with a value of 0.42 ± 0.94 MeV given by systematics [24]; and, from a mass measurement, it was found $S_{2n} = -0.14(46)$ MeV [25]. There is an indirect evidence that ^{22}C could be bound by less than 70 keV [26]. Other independent information on the binding energy of this nucleus can be obtained from the matter radius. Tanaka and collaborators [27] extracted a root-mean-square (rms) matter radius of 5.4 ± 0.9 fm from the analysis of the large reaction cross sections of ^{22}C on liquid hydrogen target at 40A MeV, by using a finite-range Glauber calculation under an optical-limit approximation. Furthermore, the two-valence neutrons occupy preferentially one $s_{1/2}$ orbital in their analysis. Such rms matter radius, taken together with the corresponding one of ^{20}C (2.98(5) fm [28]), suggest a halo neutron orbit with rms radius of 15 ± 4 fm in ^{22}C, which is constraining the S_{2n} to be below 100 keV, as shown in Ref. [29]. This value is consistent with results obtained from a shell-model