

Helium nuclei around the neutron drip line

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Neutron rich He nuclei have been investigated using the relativistic mean field approach in co-ordinate space. Elastic partial scattering cross sections for proton scattering in inverse kinematics have been calculated using the theoretically obtained density for ${}^6,8\text{He}$ and compared with the experiment. The energies of the low-lying resonance states in the neutron unstable nuclei ${}^5,7\text{He}$ have also been calculated and compared with experimental observations.

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I. INTRODUCTION

Improvement in experimental techniques in the last decades has led to the production and study of very light neutron-rich nuclei up to and even beyond the neutron drip line. One of the very interesting phenomena in such nuclei is the neutron halo [1]. The halo significantly affects different reactions involving these nuclei.

In an earlier work [2], we studied the structure of exotic even-even Be and C nuclei and calculated the elastic proton scattering cross section using the theoretical densities. In the present work, we apply the same procedure to He nuclei near the neutron drip line. These nuclei have only a few nucleons and show a very large neutron-proton ratio. The study of such nuclei is important for the effect of their extreme isospin values on the nuclear interaction. Besides the bound states in the even-even nuclei, low-energy resonance states in odd mass He nuclei beyond the drip line were also investigated.

One of our main interests lies in the prediction for neutron radius and neutron density in He nuclei. Neutron-rich He nuclei are known to exhibit neutron halos. However, the determination of the extent of the halo is ambiguous, as the information on density is model dependent in absence of direct measurements like electron scattering. For a nucleus with only a few nucleons, the bulk radius value, extracted from the experiment, may also be model dependent. A direct comparison with experimental measurements may yield a better idea about the accuracy of the calculation. For example, the calculation of a differential cross section in elastic proton scattering in inverse kinematics is expected to provide a test for the calculated densities [3].

II. METHOD

The relativistic mean field (RMF) approach is now a standard tool in low-energy nuclear structure. It has been able to explain different features of stable and exotic nuclei like

the ground state binding energy, deformation, radius, excited states, spin-orbit splitting, neutron halo, and so on [4]. It is well known that in nuclei far away from the stability valley, the single particle level structure undergoes certain changes in which the spin-orbit splitting plays an important role. RMF is particularly suited to investigate these nuclei because it is based on the Dirac Lagrangian density which naturally incorporates the spin degrees of freedom.

Different variations of the Lagrangian density, as well as different parametrizations, have been systematically investigated by many authors. In our earlier work [2] we used the density NLSH [5], known for its ability to describe nuclei near stability valley. A newer Lagrangian density, FSU Gold, which involves self-coupling of the vector-isoscalar meson as well as coupling between the vector-isoscalar meson and the vector-isovector meson, was proposed by the authors of Ref. [6]. This density was applied in our studies on proton radioactivity [7], cluster decay [8] and alpha decay [9], and so on. NL3 [10] is another force that has proved to be very useful in describing the ground state properties throughout the periodic table. Another force, NL2 [11], has been found to be successful for the description of light nuclei. In the present work, we employ all the above forces and compare the results.

In the conventional RMF + BCS approach for even-even nuclei, the Euler-Lagrange equations are solved under the assumptions of classical meson fields, time reversal symmetry, no-sea contribution, and so on. Pairing is introduced under the BCS approximation. Usually the resulting equations are solved in a harmonic oscillator basis. However, in exotic nuclei, the basis expansion method using the harmonic oscillator, because of its incorrect asymptotic properties, faces problems in describing the loosely bound halo states. A solution of the Dirac and Klein Gordon equations in coordinate space may be preferable to describe the weakly bound states. Such calculations exist in the Relativistic Hartree-Bogoliubov (RHB) approximation in r -space.

The RHB calculations, or their nonrelativistic counterparts Hartree-Fock-Bogoliubov equations, are very involved and time consuming. Interested readers are referred to the calculation of the authors of Ref. [12]. Particularly important are the relativistic continuum Hartree-Bogoliubov calculations

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[13], which take the continuum into account. A simpler approximation, introduced by the authors of Refs. [14–16], takes into account the effect of the resonant continuum through the scattering wave functions located in the region of the resonant states in the nonrelativistic picture. The cases of zero range and finite range pairings have also been investigated and the importance of the truncation of the quasiparticle space for the zero range pairing interaction has been highlighted in the above works.

RMF equations involving continuum states have also been solved [17,18] with scattering wave functions. All these calculations have taken into account the width of the continuum levels also. For example, Cao and Ma [18] also compared their results with those from calculations with zero width. They concluded that the pairing gaps, the Fermi levels, the pairing correlation energies, and the binding energies are considerably affected by proper consideration of the width of the resonant states. Particularly, near the neutron drip line, this effect is expected to be very important.

We used the above coordinate space RMF + BCS approach earlier [2,19] to study neutron-rich nuclei in different mass regions. The proximity of the neutron-rich nuclei to the drip line necessitates one to consider the effect of the positive energy states. The widths of the positive energy levels have been taken into account in the present work. We confined our calculation to spherical approximation as He nuclei are expected to be spherical. Odd nuclei were investigated in the tagged approximation.

For the solution of the equations in coordinate space, the mesh size has been taken as 0.04 fm. We assume the nuclear interaction to vanish at a radius of 14 fm. We checked that an increase in the last quantity to 20 fm keeps the results almost unchanged. The total energy varies by less than 0.02%, and the neutron radius by less than 1%. Usually the strength of the pairing interaction is chosen to reproduce the pairing energy in RHB calculations [17]. However, in our calculation the strength of the zero range volume pairing force is taken as 400 MeV-fm³ for neutrons from systematics as it was found to explain the trend in binding energy in very light nuclei reasonably well. For example, in Table I we list the FSU Gold results for binding energy in a few very light nuclei. For Be nuclei, the proton pairing strength was taken as 200 MeV-fm³. It should be mentioned that the result for ¹⁰Be is for a deformed calculation in the method followed by the authors of Refs. [2,20]. In Ref. [2], we found ¹⁰Be to be strongly deformed. It has been also observed that changes of the order of 10% in the value of the neutron pairing strength do not affect our conclusions appreciably.

As pointed out by Sandulescu *et al.* [17], in the RHB equations the pairing cutoff is usually very large allowing the quasiparticles to scatter over a very large energy. In contrast, in the RMF + BCS calculations, only a few resonant states around zero energy are included. In our case, we included only the states up to the *p* shell in the RMF calculation. Thus the maximum quasiparticle energy corresponded to the $1s_{1/2}$ state and the cutoff, to approximately 25 MeV.

Electron scattering, the most direct method for measuring nuclear density, is difficult to apply far away from the valley of stability. Elastic proton scattering in inverse kinematics

TABLE I. Binding energy per nucleon in a few very light nuclei using FSU Gold Lagrangian. Pairing strength for protons and neutrons have been taken as 200 MeV-fm³ and 400 MeV-fm³, respectively. See text for details.

Nucleus	Binding Energy (MeV)	
	Expt.	Theo.
⁷ Li	5.606	5.535
⁹ Li	5.038	5.121
¹⁰ Be	6.498	6.636
¹² Be	5.721	5.696
¹⁴ Be	4.994	4.854

provides an alternate test for the calculated densities [3]. The optical model potential is obtained using an effective interaction, derived from nuclear matter calculation, in the local density approximation (i.e., by substituting the nuclear matter density with the calculated density distribution of the finite nucleus). In the present case microscopic nuclear potentials have been obtained by folding two effective interactions, discussed later, with the microscopic densities obtained in the RMF calculations. The Coulomb potential has been similarly obtained by folding the Coulomb interaction with the microscopic proton density.

A common effective interaction DDM3Y [21,22] was obtained from a finite-range energy-independent M3Y interaction by adding a zero-range energy-dependent pseudopotential and introducing a density-dependent factor. This interaction was employed widely in the study of nucleon-nucleus as well as nucleus-nucleus scattering, the calculation of proton radioactivity, and so on. The density dependence may be chosen as exponential [21] or be of the form $C(1 - \beta\rho^{2/3})$ [22]. In this particular work we selected the latter form. The constants, obtained from nuclear matter calculation [23] as $C = 2.07$ and $\beta = 1.624 \text{ fm}^2$, were used in our calculation. For scattering we have taken the real and the imaginary parts of the potential as 0.8 times and 0.2 times the DDM3Y potential. In both the calculations, the spin-orbit potential was chosen from the Scheerbaum prescription [24]. The calculations were performed with the computer codes MOMCS [25] and ECIS95 [26] assuming spherical symmetry.

To check our results, we employed another interaction, the JLM interaction of Jeukenne, Lejeune, and Mahaux (JLM) [27] in which further improvement was incorporated in terms of the finite range of the effective interaction by including a Gaussian form factor. We used the global parameters for the effective interaction and the respective default normalizations for the potential components from Refs. [25,28] with Gaussian range values of $t_{\text{real}} = t_{\text{imag}} = 1.2 \text{ fm}$. No search has been performed on any of these parameters.

III. RESULTS

A. Even-even isotopes—ground state energy and density

The two neutron-rich even-even He nuclei, stable against neutron emission, are ^{6,8}He. Experimental measurements exist for binding energy and radius values in these nuclei. The radius

TABLE II. Binding energy per nucleon and radius values in ${}^6,8\text{He}$ compared with experimental values. Experimental binding energy values are from the compilation [37]. Experimental proton radii are from laser spectroscopy study [36]. Experimental rms radii values are the results of Glauber model analysis in the optical limit [34]. See text for radius values from other measurements.

		${}^6\text{He}$	${}^8\text{He}$
B.E.(MeV)	Expt.	4.878	3.926
	NLSH	5.831	4.669
	FSU Gold	5.507	4.222
	NL3	5.890	4.780
	NL2	5.161	3.765
r_p (fm)	Expt.	2.068(11)	1.929(26)
	NLSH	1.86	1.83
	FSU Gold	1.88	1.86
	NL3	1.92	1.88
	NL2	1.89	1.88
r_n (fm)	Expt.	2.72	
	NLSH	2.92	2.83
	FSU Gold	3.12	3.07
	NL3	3.11	2.89
	NL2	3.63	3.69
r_{rms} (fm)	Expt.	2.48(3)	2.52(3)
	NLSH	2.61	2.61
	FSU Gold	2.76	2.81
	NL3	2.77	2.67
	NL2	3.16	3.33

values have been measured in different ways. Using proton elastic scattering Kiselev *et al.* [29] measured the matter radii in ${}^6,8\text{He}$ to be 2.37(5) fm and 2.49(4) fm, respectively. Tanihata *et al.* [30] obtained the matter radii of ${}^6,8\text{He}$ as 2.33(4) and 2.49(4) fm, respectively. A reanalysis [31] of the same data yielded the value 2.71(4) fm for ${}^6\text{He}$. Lapoux *et al.* found a radius of 2.5 fm from inelastic scattering data [32] and 2.55 fm from elastic scattering [33] for ${}^6\text{He}$. Finally, a Glauber model analysis in the optical limit yielded the values 2.48(3) and 2.52(3) fm [34] for ${}^6,8\text{He}$, respectively. In another experiment, Egelhof *et al.* [35] deduced the values to be 2.30(7) and 2.45(7) fm, respectively, from proton scattering at intermediate energy. Using the proton radius value quoted in Table II, measured by laser spectroscopy [36], the experimental neutron radii are seen to lie within the range 2.41–2.98 fm for ${}^6\text{He}$ and 2.60–2.69 fm for ${}^8\text{He}$.

In Table II, our results for binding energy and radius values in ${}^6,8\text{He}$ are given and compared with experimental measurements wherever available. There is a basic difference between the single particle levels predicted by the different forces. The two forces NL2 and FSU Gold, which produce better agreements with the binding energy values, predict the level $\nu p_{1/2}$ to be in the continuum in ${}^8\text{He}$. The other two forces predict it to be very weakly bound. We find that NL2 predicts both ${}^6,8\text{He}$ to have a negative two-neutron separation energy at variance with experimental observations.

As already mentioned, the effect of the width of the levels in the continuum has been incorporated in our calculation.

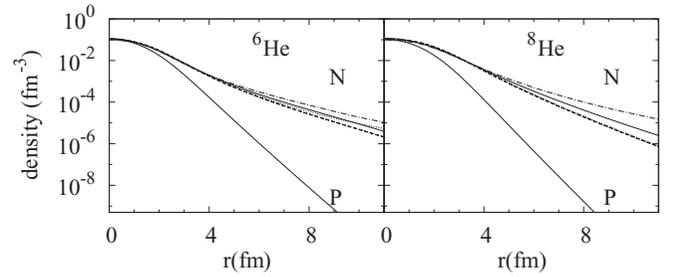


FIG. 1. Calculated proton and neutron densities in ${}^6,8\text{He}$ for the force FSU Gold (solid line), NLSH (dashed line), NL3 (dotted line), and NL2 (dash-dotted line). The proton density is nearly identical in all the calculations.

For example, FSU Gold predicts the level $\nu p_{1/2}$ to be in the continuum in ${}^6\text{He}$ with a very large width of 1.8 MeV, which, in ${}^8\text{He}$, comes down to 0.28 MeV. Obviously, the angular momentum of the $p_{1/2}$ state being small, the centrifugal barrier cannot localize the state very effectively. The effect of the resonant level on the binding energy is very small (less than 0.05% in the case of ${}^6\text{He}$) as the occupancy of $p_{1/2}$ level is very small. However, even this small occupancy has a larger effect on the neutron radius concerned because an unbound resonant level has a radius much larger than the bound state. Thus, we find that the effect of including the effect of the level width increases the neutron radius by 0.5%. Small though the number is, it is comparable to the experimental errors in measurements of rms radii in these nuclei.

The experimental radii values that have been shown in Table II are from Glauber model analysis [34] and laser spectroscopy [36]. The calculated results are in reasonable agreement with experimental measurements given the fact that the number of nucleons is very small and the mean field approach may not be very accurate. One can see that the force NL2, which gives the least binding energy, also predicts neutron radii values to be considerably larger than the other forces.

The calculated proton and the neutron densities in ${}^6,8\text{He}$ are shown in Fig. 1. One interesting observation is that at large radius, the density in ${}^6\text{He}$ decreases more slowly than in ${}^8\text{He}$. This is the reason that the neutron radius of the latter nucleus is smaller than that of the former. This is obviously due to the fact that the level $\nu p_{1/2}$ is either bound or has very small positive energy in ${}^8\text{He}$. The two forces, NLSH and NL3, which predict this level to be bound in ${}^8\text{He}$, show a smaller neutron radius as expected.

In view of the ambiguity of the radius extracted from different measurements, we calculated the differential cross sections directly using two standard interactions, JLM and DDM3Y, for some of the actual experiments. All the densities obtained from different Lagrangians were used. In Fig. 2 we select the experimental values for ${}^6,8\text{He}$ scattering from Refs. [38–40], respectively and compare with our calculation.

As we have seen, the nuclear densities from NLSH, NL3, and FSU Gold are very similar, while NL2 shows a more diffused neutron density and larger neutron radius. However, we find that in the region where experimental data are available, there is very little difference between the predictions

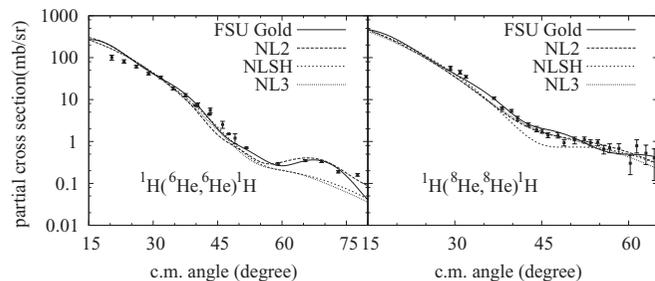


FIG. 2. Partial cross section for the elastic proton scattering in inverse kinematics using the DDM3Y interaction. The projectile energies of ${}^6\text{He}$ and ${}^8\text{He}$ are 71 MeV/nucleon and 72 MeV/nucleon, respectively.

of the forces. The force FSU Gold shows a larger cross section at very large angles, a region where data are not yet available. The DDM3Y interaction describes the data much better, particularly at large angles. The results of the JLM interaction (not shown in the figure) show a smoother behavior maintaining the overall trend. In ${}^6\text{He}$, the results for NL3 and NLSH densities can be brought closer to experiments by modifying parameters such as normalization factors of the potential or the ranges in the Gaussian form factors in the JLM approach. However, no attempt has been made to fit the data and global parameters have been adopted in the present work. From these results, it is possible to conclude that the density has been predicted reasonably well in the present calculation. Results for other energies show similar agreement.

B. Odd isotopes—resonance states

As shown above, the present method provides a reasonable description of the even-even nuclei ${}^{6,8}\text{He}$. We note that these nuclei are stabilized against neutron emission by the pairing force. We next extend our study to the odd nuclei ${}^{5,7}\text{He}$, which are unstable against neutron emission.

The most important experimental information in these odd isotopes are the energies of some of the states in the continuum. It is possible to calculate the energy of some pure single particle resonances and compare with the experiment. Though the total energy is not very accurately predicted, we expect the resonance energy, being the difference of two absolute energy values, to be more accurate. Thus, it is possible to probe the structure of nuclei beyond the neutron drip line. We study the one quasiparticle resonances built on the single particle states $1p_{3/2}$ and $1p_{1/2}$. They correspond to the observed states built on the ground state of the even-even core plus the last odd neutron in the single particle orbits mentioned above.

As we will see, the experimental situation is rather unclear in these nuclei. The measurements about which there are some degree of agreement between different experiments are the energies of the $3/2^-$ resonance. We find that the FSU Gold Lagrangian density provides the best overall results for these values. The NLSH results are comparable but slightly poorer. The results from NL2 are much worse while NL3 predicts ${}^7\text{He}$ to be stable against neutron emission. For odd mass He nuclei, we present the results for the FSU Gold density only.

To very briefly summarize the experimental situation in ${}^5\text{He}$, the lowest energy states are known to arise out of ground state of the even-even core coupled to a $p_{3/2}$ neutron. In ${}^5\text{He}$, this state occurs at a resonance energy around 0.8 MeV. Tilley *et al.* [41] placed it at 0.798 MeV with a width 0.648 MeV and found another resonance with spin-parity $1/2^-$ at 2.068 MeV with width 5.57 MeV. Although the results for the ground state resonance was in reasonable agreement with earlier measurements [42], the situation in $1/2^-$ was different. Here, previous work placed the resonance at 4.089 MeV. In a recent analysis [43] of an older work [44], the ground state was found at a resonance energy of 0.741(4) MeV with width 0.655 MeV.

Theoretically, we find that ${}^5\text{He}$ is unstable against neutron emission. The lowest state is the $3/2^-$ resonance calculated to be at 0.92 MeV energy, in good agreement with the experiment. However, the $1/2^-$ resonance is predicted to be at a resonance energy of 4.47 MeV, at a much higher energy compared with the result of the authors of Ref. [41]. Some other theoretical investigations also predict a higher energy resonance for the $1/2^-$ state. For example, the continuum shell model calculation of Volya and Zelevensky [45] predicted the $3/2^-$ and the $1/2^-$ resonances at 0.99 and 4.93 MeV, respectively.

In ${}^7\text{He}$, the $3/2^-$ resonance is known to occur at an energy of approximately 0.45 MeV and has a width of $\Gamma = 0.15$ MeV [46]. A resonant state at $E^* = 2.9$ MeV with width around $\Gamma = 2$ MeV [46] was interpreted as an odd nucleon coupled to the 2^+ excited state of the core. Another resonant state at $E^* = 0.6(0.1)$ MeV with $\Gamma = 0.75$ MeV observed in the breakup of ${}^8\text{He}$ [47] was suggested to arise out of coupling of $p_{1/2}$ nucleon to the ${}^6\text{He}$ ground state. Skaza *et al.* [48] observed the $1/2^-$ resonance at $E^* = 0.9(0.5)$ MeV with $\Gamma = 1.0$ MeV. Indications of a low-energy narrow resonance was also observed by other workers [49]. However, a study [50] using isobaric analog states did not observe the last resonance, but reported a broad $1/2^-$ resonance at 2.2 MeV. Ryezayeva *et al.* [51] also did not find any low energy $1/2^-$ resonance, but observed indications of a broad resonance at 1.45 MeV. Wuosmaa *et al.* [46,52] observed a possible resonance at 2.6 MeV excitation energy, but no indication of any $1/2^-$ resonance at lower energy. Aksyutina *et al.* [43] found the resonance energy of the ground state to be 0.388 (2) MeV and width 0.190 MeV. They could not draw any unambiguous conclusion about the possibility of a resonance around 1 MeV.

Our calculations place the $3/2^-$ resonance at 0.63 MeV energy. It appears at a higher energy possibly because the experimental state also has a contribution from $p_{1/2}$ orbit coupled to the 2^+ state of ${}^6\text{He}$. The $1/2^-$ resonance is calculated to be at 2.09 MeV resonance energy (i.e., 1.46 MeV excitation energy). Thus our results agree with the experiment of Ryezayeva *et al.* [51] and possibly with Skaza *et al.* [48], but not with other measurements. Other theoretical calculations also do not lead to any unambiguous conclusion. The continuum shell model study [45] shows the ground state resonance $3/2^-$ at 0.36 MeV and the excited $1/2^-$ state around an excitation energy of 3.3 MeV. However, a recoil corrected continuum shell model study of Halderson [53] places the resonance energy around 1 MeV.

IV. SUMMARY

To summarize, the structure of neutron-rich He nuclei was investigated using the RMF approach in coordinate space. The binding energy and radii values show reasonable agreement with the experiment. Optical model potentials were calculated from effective interactions applied in finite nuclei in the folding model. Elastic partial scattering cross sections for proton scattering in inverse kinematics were calculated using the theoretically obtained density for ${}^6,8\text{He}$ and compared with some available experiments. The energies of the low-lying resonance states in the neutron

unstable nuclei ${}^5,7\text{He}$ were also calculated and compared with experiments.

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