Nonlinear relativistic mean-field theory studies on He isotopes

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Abstract: The ground state properties of He isotopes are studied in the nonlinear relativistic mean-field (RMF) theory with force parameters NL-SH and TM2. The modified Glauber model is introduced as a gatekeeper to check the calculations. The investigation shows that the RMF theory provides a good description on the properties of He isotopes. The many-body space information of ^{4}He + neutrons is obtained reliably. As a product, the calculation gives strong evidence for a neutron halo in ^{5}He.

Key words: He isotopes, RMF, glauber model, nuclear structure

PACS: 21.10.Gv, 21.60.Jz, 25.60.Dz   **DOI:** 10.1088/1674-1137/38/12/124102

1   Introduction

The ^{7}He unbound ground state was observed more than 40 years ago [1]; however, the positions and quantum numbers of excitations remain uncertain. The excited states of ^{7}He can decay not only to ^{6}He+n channels, but also to ^{5}He+2n and ^{4}He+3n channels. This broad resonance condition makes it difficult to separate the excitations. Contradictions remain in the experiments, such as energy levels with spins of $5/2^-$ and $1/2^-$ [2–8]. Theoretically, ab initio calculations are often employed to describe the many-body decay properties of ^{7}He; however, it is still unable to satisfy the multi-particle decay conditions for all open channels, because when people discuss the structure of ^{7}He resonances, it is simultaneously important to describe the structure of ^{5}He and ^{6}He [9–16].

2   Formalism of the nonlinear relativistic mean-field theory and the structure of the He isotopes

The nonlinear relativistic mean-field (RMF) theory has produced very reliable results on the nuclear structure during the past 30 years [17–20]. Therefore, in this article, we will calculate the ground state properties of $^{5-7}$He by using this theory. Because the RMF theory is a standard theory and detailed formalism can be found in a number of Refs. [17–23], here we shall briefly describe the framework of the theory. In the RMF, the starting point of the description of the many-body problem is the local Lagrangian density

$$\mathcal{L} = \bar{\Psi}(i\gamma^\mu\partial_\mu - M)\Psi - g_\sigma\sigma\Psi - g_\omega\Psi\gamma^\mu\omega_\mu\Psi$$
$$- g_\rho\Psi\gamma^\mu\rho_\mu^\alpha\tau^\alpha\Psi + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3$$
$$- \frac{1}{4}g_3\sigma^4 - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}R^{\alpha\mu\nu}\times R_{\mu\nu}^\alpha$$
$$+ \frac{1}{2}m_\rho^2\rho^{\alpha\mu}\times\rho_\mu^\alpha - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}e\bar{\Psi}\gamma^\mu A^\mu(1-\tau^3)\Psi, \quad (1)$$

with relations

$$\Omega^{\mu\nu} = \partial^\mu\omega^\nu - \partial^\nu\omega^\mu, \quad (2)$$

$$R^{\alpha\mu\nu} = \partial^\mu\rho^{\alpha\nu} - \partial^\nu\rho^{\alpha\mu} + g_\rho\epsilon^{abc}\rho^{b\mu}\rho^{c\nu}, \quad (3)$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu, \quad (4)$$

where ρ_μ^α, σ, and ω_μ denote the meson fields, m with subscripts ρ, σ, and ω denotes their masses, respectively. The Ψ and M represent the nucleon field and rest mass. The A^μ is the photon field, which is responsible for the electromagnetic interaction $e^2/4\pi = 1/137$. The g with subscripts 2, 3, ρ, σ, and ω represents the strengths of the coupling. The Pauli matrices are given by τ. In practice, the above parameters such as meson masses and coupling strengths are obtained through the fitting of experimental observables. We will carry out numerical calculations with two sets of force parameters: NL-SH [23] and TM2 [24]. These two sets of force parameters are proposed by the fitting of properties ranging from light to heavy nuclei, even unstable nuclei.

The numerical results of nuclei $^{5-8}$He are listed in Tables 1 and 2, where B(MeV), R_m (fm), R_p (fm), and R_n

(fm) are the binding energy, root-mean-square (RMS) radii of matter, proton, and neutron distributions. In order to explain the structure of He isotopes more fully, we also list the single particle energy $-\varepsilon$(MeV), and the mean-square radius of $1p_{3/2}$ neutron R^2 (fm^2), which reflects the many-body space information of ^{4}He+X neutrons (Xn, X=1, 2, 3.). It is seen that the calculations with NL-SH and TM2 force parameters almost exhibit the same results in the two Tables. As is shown by the single particle energy, one can find that $1p_{3/2}$ neutrons are very weakly bound in He isotopes and ^{5,6}He exhibits obviously as the neutron halo structure. It also reaches the same conclusion from the R^2, because $R^2(1p_{3/2})$(n)=15.64±0.89 fm and =12.62±0.20 fm in ^{5}He and ^{6}He are much larger as compared with the mean-square radius of all neutrons $R_n^2 \approx 7.80$ fm. The values of $R^2(1p_{3/2})$(n) are the average values of the calculations listed in Tables, the errors are obtained from the differences between the calculations with NL-SH and TM2 force parameters. Experimentally, the ^{6}He has been already proved to be a halo structure [25, 26]. In Tables 1

and 2, we also show the calculations of ^{8}He, the small R^2, as compared with that of ^{5}He and ^{6}He, indicates that ^{8}He has a skin structure, which is as good as the conclusions of the experiments [26].

Table 1.　The RMF results with NL-SH.

	^{5}He	^{6}He	^{7}He	^{8}He
B/MeV	33.21	33.43	34.82	37.34
R_m/fm	2.60	2.68	2.71	2.74
R_p/fm	1.88	1.86	1.84	1.83
R_n/fm	2.80	2.84	2.83	2.83
R^2/fm^2	16.52	12.81	11.32	10.55
$-\varepsilon(1s_{1/2})$(p)	20.32	24.54	28.86	33.14
$-\varepsilon(1s_{1/2})$(n)	19.42	20.85	22.21	23.48
$-\varepsilon(1p_{3/2})$(n)	0.81	1.77	2.74	3.68

Table 2.　The RMF results with TM2.

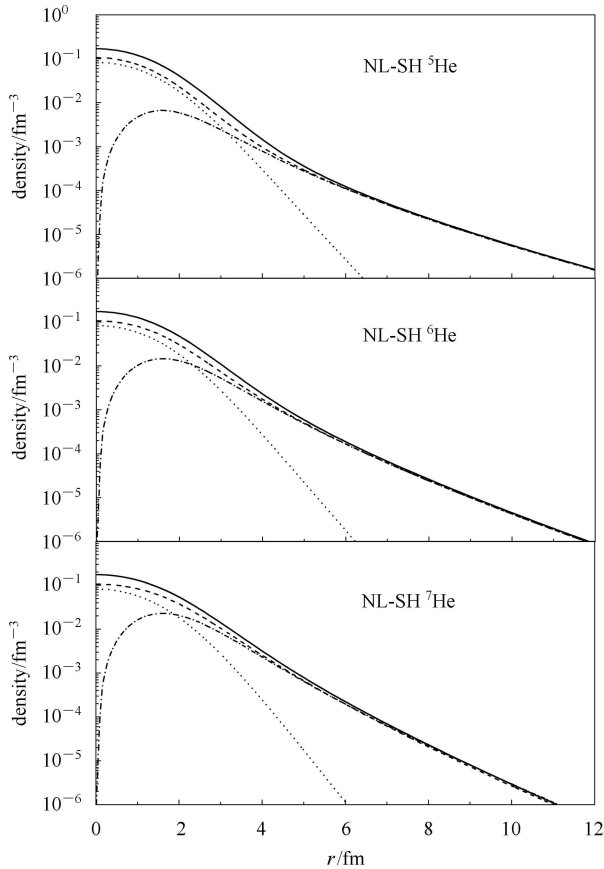|	^{5}He	^{6}He	^{7}He	^{8}He
B/MeV	33.52	34.07	35.74	38.39
R_m/fm	2.53	2.65	2.71	2.76
R_p/fm	1.88	1.86	1.84	1.83
R_n/fm	2.69	2.80	2.83	2.85
R^2/fm^2	14.75	12.42	11.35	10.76
$-\varepsilon(1s_{1/2})$(p)	21.51	25.94	30.40	34.74
$-\varepsilon(1s_{1/2})$(n)	20.28	21.71	23.04	24.24
$-\varepsilon(1p_{3/2})$(n)	1.15	2.05	2.94	3.78

Fig. 1.　The density distributions of proton, neutron, matter, and Xn of He isotopes in the RMF theory with TM2 force parameters. The solid, dashed, dotted, and dash-dotted curves are the matter, neutron, proton, and Xn respectively.
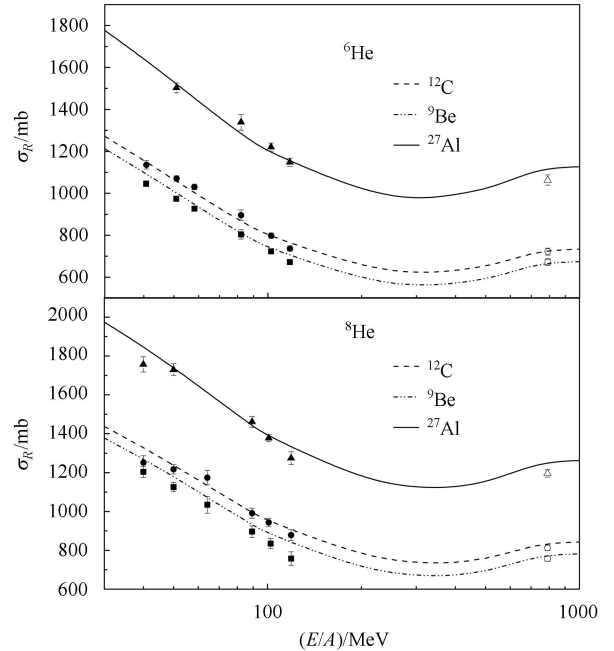

Fig. 2.　The reaction cross sections of ^{6,8}He as a function of beam energy. The open symbols denote data from Ref. [28]. The closed symbols denote the data from Ref. [26]. The curves are calculated by using the Glauber model in conjunction with the RMF theory with force parameter of NL-SH.

In Fig. 1, we draw the density distributions of proton, neutron, matter and Xn in ^{5}He, ^{6}He and ^{7}He. In the Fig., the solid, dashed, dotted and dash-dotted curves are the densities of matter, neutron, proton, and Xn respectively. It is evident that the halo structures in ^{5}He and ^{6}He as their density distribution of neutrons have a long tail. However, people also notice that due to the ambiguity of the definition of the halo structure, we cannot conclude whether ^{7}He is a halo or not. In order to check the reliabilities of the results deeply, we introduce the modified optical Glauber model [27] and the experimental reaction cross sections as gatekeepers. The Glauber model is often used to analyze the experimental reaction cross sections. It is a useful tool to extract the density distribution of the nuclei from the reaction cross sections. Thus the Glauber model is also an effective tool to check the reliabilities of the density distribution. In the calculations of the reaction cross sections of ^{6,8}He + ^{12}C, ^{9}Be, and ^{27}Al, the density distributions of the RMF theory with NL-SH and TM2 force parameters are used as the input parameters in the Glauber model, and the theoretical reaction cross sections have only a little dif-ference between NL-SH and TM2. The outcomes with NL-SH parameter are shown in Fig. 2. It is concluded from Fig. 2 that the RMF theory with force parameters NL-SH and TM2 provides a good description on the properties of He isotopes. As a conclusion, the RMF theory also predicts a one-neutron halo in ^{5}He.

3 Summary

In conclusion, we have calculated the ground state properties of He isotopes using the RMF theory with NL-SH and TM2 force parameters. It is shown that neutrons in $1p_{3/2}$ state in He isotopes are weakly bound. The ^{5}He exhibits a halo structure, and the size of neutron halo in it is larger than that in ^{6}He. The introduction of the Glauber model confirms the reliabilities of the investigations of the RMF theory. So finally, we believe that the many-body space information of $^{5-7}$He is reliable.

References

1 Stokes R H, Young P G. Phys. Rev. Lett., 1967, **18**: 611
2 Korsheninnikov A A et al. Phys. Rev. Lett., 1999, **82**: 3581
3 Bohlen G et al. Phys. Rev. C, 2001, **64**: 024312
4 Meister M et al. Phys. Rev. Lett., 2002, **88**: 102501
5 Wuosmaa A H et al. Phys. Rev. C, 2005, **72**: 061301
6 Boutachkov P et al. Phys. Rev. Lett., 2005, **95**: 132502
7 Skaza F et al. Phys. Rev. C, 2006, **73**: 044301
8 Ryezayeva N et al. Phys. Lett. B, 2006, **639**: 623
9 Navrátil P, Barrett B R. Phys. Rev. C, 1998, **57**: 3119
10 Pieper S C, Wiringa R B, Carlson J. Phys. Rev. C, 2004, **70**: 054325
11 Volya A, Zelevinsky V. Phys. Rev. Lett., 2005, **94**: 052501
12 Hagen G, Hjorth-Jensen M, Vaagen J S. Phys. Rev. C, 2005, **71**: 044314
13 Michel N, Nazarewicz W, Ploszajczak M. Phys. Rev. C, 2007, **75**: 031301
14 Hagen G et al. Phys. Lett. B, 2007, **656**: 169
15 Myo T, Katō K, Ikeda K. Phys. Rev. C, 2007, **76**: 054309
16 Myo T, Ando R, Katō K. Phys. Rev. C, 2009, **80**: 014315
17 Horowitz C J, Serot B D. Nucl. Phys. A, 1981, **368**: 503
18 Reinhard P G et al. Z. Phys. A, 1986, **323**: 13
19 Patra S K. Nucl. Phys. A, 1993, **559**: 173
20 REN Zhong-Zhou et al. Phys. Rev. C, 1996, **53**: 572(R)
21 Reinhard P G. Rep. Prog. Phys., 1989, **52**: 439
22 Furnstahl R J, Price C E. Phys. Rev. C, 1989, **40**: 1398
23 Sharma M M, Nagarajan M A, Ring P. Phys. Lett. B, 1993, **312**: 377
24 Sugahara Y, Nix J R. Nucl. Phys. A, 1994, **476**: 557
25 Gasques L R et al. Phys. Rev. C, 2003, **67**: 024602
26 Takechi M et al. AIP Conf. Proc., 2006, **891**: 187–191
27 Takechi M et al. Phys. Rev. C, 2009, **79**: 061601(R)