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Neutron halos in O isotopes

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The ground state properties of O isotopes have been studied in the nonlinear relativistic mean-field theory with NL-SH parameters. Neutron halos in ^{24}O, ^{26}O, and ^{28}O are predicted. The variation of the spin-orbit splitting with the neutron excess for O isotopes is also investigated with both NL-SH and NL1 parameters. Detailed comparison and analysis on the results are given.

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Ten years ago, Tanihata *et al.* [1] found by the nucleus-nucleus collision experiment that ^{11}Li has an abnormally large interaction cross section and concluded that ^{11}Li has an extraordinarily large matter root-mean-square (RMS) radius. Hansen and Jonson [2] have performed pioneer work on ^{11}Li and pointed out there exist neutron halos. Mittig *et al.* [3], Saint-Laurent *et al.* [4], and Kobayashi *et al.* [5] have further found in a series of experiments that there exist neutron halos in ^{11}Li, ^{11,14}Be, and ^{17}B. Very recently it was also reported [6] that there exist neutron halos in medium and heavy nuclei. Studies on halo nuclei have been a hot point in nuclear physics [7–20].

Until now, detailed studies both theoretical and experimental were performed on ^{6,8}He, ^{11}Li, ^{11,14}Be, and ^{17}B. Here we shall study the ground state properties of O isotopes theoretically. Although ^{26,28}O have not been produced in experiments [21,22] up to now, many mass formulas [23] and the nuclear shell model calculations [24] suggest them to be bound. Hansen [22] also considers that they may be weakly bound. We shall carry out systematic calculations on O isotopes in the nonlinear relativistic mean-field theory with NL-SH parameters so that one tests its prediction by future experiments.

The nonlinear relativistic mean-field theory (RMF) with σ, ω, and ρ mesons has described with great success the ground state properties of nuclei in recent years [25–30]. Very recently, Sharma *et al.* [31] proposed a new set of parameters, NL-SH parameters, and found they can very well reproduce not only the binding energy but also the RMS radii of proton and neutron distributions for some isotopes. They have also shown for medium and heavy nuclei that NL-SH parameters work well even near the drip line.

The RMF theory being a standard theory, here we briefly describe the framework of the RMF with σ, ω, and ρ mesons. The details can be found in Refs. [25–31]. Our starting point for the description of the nuclear many-body problem is the effective Lagrangian density for the interacting nucleons, the σ, ω, and ρ mesons and photons,

$$\begin{aligned}\mathscr{L}=&\bar{\Psi}(i\gamma^{\mu}\partial_{\mu}-M)\Psi-g_{\sigma}\bar{\Psi}\sigma\Psi-g_{\omega}\bar{\Psi}\gamma^{\mu}\omega_{\mu}\Psi\\&-g_{\rho}\bar{\Psi}\gamma^{\mu}\rho^{a}_{\mu}\tau^{a}\Psi+\tfrac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma-\tfrac{1}{2}m^{2}_{\sigma}\sigma^{2}-\tfrac{1}{3}g_{2}\sigma^{3}-\tfrac{1}{4}g_{3}\sigma^{4}\\&-\tfrac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu}+\tfrac{1}{2}m^{2}_{\omega}\omega^{\mu}\omega_{\mu}-\tfrac{1}{4}R^{a\mu\nu}\cdot R^{a}_{\mu\nu}\\&+\tfrac{1}{2}m^{2}_{\rho}\rho^{a\mu}\cdot\rho^{a}_{\mu}-\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu}-e\bar{\Psi}\gamma^{\mu}A^{\mu}\tfrac{1}{2}(1-\tau^{3})\Psi\end{aligned}\tag{1}$$

with

$$\Omega^{\mu\nu}=\partial^{\mu}\omega^{\nu}-\partial^{\nu}\omega^{\mu},\tag{2}$$

$$R^{a\mu\nu}=\partial^{\mu}\rho^{a\nu}-\partial^{\nu}\rho^{a\mu}+g_{\rho}\epsilon^{abc}\rho^{b\mu}\rho^{c\nu},\tag{3}$$

$$F^{\mu\nu}=\partial^{\mu}A^{\nu}-\partial^{\nu}A^{\mu},\tag{4}$$

where the meson fields are denoted by σ, ω_{μ}, and ρ^{a}_{μ} and their masses are denoted by m_{σ}, m_{ω}, and m_{ρ}, respectively. The nucleon field and rest mass are denoted by Ψ and M. A_{μ} is the photon field which is responsible for the electromagnetic interaction, $e^2/4\pi=1/137$. The effective strengths of the coupling between the mesons and nucleons are, respectively, g_{σ}, g_{ω}, and g_{ρ}. The isospin Pauli matrices are written as τ^{a}, τ^{3} being the third component of τ^{a}. Under the mean-field approximation, the meson fields are considered as classical fields and they are replaced by their expectation values in vacuum. We solve the nuclear system using the above Lagrangian [25,27,29]. Using procedures similar to those of Refs. [25,27,29], we have a set of coupled equations for mesons and nucleons and they will be solved consistently by the iteration. After the final solutions are obtained, the total binding energy and other quantities will be calculated from the wave function. We have checked our code of the nonlinear mean-field calculation for some nuclei and found it agrees with the result of Sharma *et al.* [31].

At present all nuclear models have been used mainly to study nuclei near the β-stable line. As they are generalized to nuclei far from stability, careful tests should be done. Therefore we begin the RMF calculation with NL-SH parameters from ^{16}O to ^{28}O and investigate its reliability by comparing the difference between the theoretical binding energy and the experimental one. The results are listed in Table I, where

TABLE I. The ground state properties of O isotopes.

^{A}X	B (MeV)	R_p (fm)	R_n (fm)	B [30] (MeV)	B (Expt.) (MeV)
^{28}O	177.40	2.70	3.50		?
^{26}O	172.94	2.65	3.40		?
^{24}O	170.46	2.60	3.24	168.72	168.48±0.31
^{22}O	163.29	2.57	2.99	160.04	162.03
^{20}O	150.18	2.57	2.89	150.08	151.37
^{18}O	138.56	2.57	2.75	141.07	139.81
^{16}O	128.56	2.58	2.55	127.26	127.62

TABLE II. Levels of neutrons in *s*-*d* shell and corresponding mean-square radii.

^AX	ε $(1d_{5/2})$	ε $(2s_{1/2})$	ε $(1d_{3/2})$	$\overline{R^2}$ $(1d_{5/2})$	$\overline{R^2}$ $(2s_{1/2})$	$\overline{R^2}$ $(1d_{3/2})$
^{28}O	8.57	5.33	2.81	12.99	18.80	17.10
^{26}O	8.06	4.73	1.87	12.55	19.09	17.80
^{24}O	7.56	4.06		12.12	19.55	

the first column is the nucleus and second column is the theoretical binding energy. The RMS radii of proton and neutron distributions are given in the third and fourth columns. In the fifth and sixth columns, we have listed Patra's result [30], which is obtained in the RMF theory with NL1 parameters and the experimental data of the binding energy [32,33]. It is seen that the nonlinear RMF theory with NL-SH parameters is as good as the nonlinear RMF theory with NL1 parameters [30]. The difference of the binding energy between our results and experimental data is less than 2 MeV. (The total energy is between about 100 and 170 MeV.) The purpose of the NL-SH parameters by Sharma *et al.* [31] was to improve the prediction of the RMS radii of proton and neutron distribution by the nonlinear RMF theory. In this case, we consider that the nonlinear RMF theory with NL-SH parameters can be used to predict the ground state properties of O isotopes.

It is seen from Table I that together with the increase of neutron number, the RMS radius of neutron distributions will increase and this indicates that the appearance of neutron halos in O isotopes is possible. In order to elucidate whether there are neutron halos, in Table II, we have given the single particle energy ϵ (MeV) and the corresponding mean-square radius $\overline{R^2}$(fm^2) of neutrons in $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ for ^{24}O, ^{26}O, and ^{28}O. For ^{28}O, it is seen that the mean-square radius of neutrons in $1d_{5/2}$ $\overline{R^2}(1d_{5/2})=12.99$ fm^2 is close to the square of the RMS radius of all neutrons $R_n^2=12.25$ fm^2. It is quite evident that the mean-square radii of neutrons in $2s_{1/2}$ and $1d_{3/2}$ $\overline{R^2}(2s_{1/2})=18.8$ fm^2 and $\overline{R^2}(1d_{3/2}=17.1$ fm^2 are large as compared to the square of the RMS radii of all neutrons $R_n^2=12.25$ fm^2. We conclude that there are six halo neutrons in ^{28}O. There are four and two halo neutrons for ^{26}O and ^{24}O, respectively, by similar arguments. It is important to note that in Table II the mean-square radius of halo neutrons in $2s_{1/2}$ is close to that in $1d_{3/2}$ for halo nuclei although the level $2s_{1/2}$ is deeper than the level $1d_{3/2}$. This is due to the fact that the mean-square radius for a level is related to the detailed behavior of the wave function (especially its behavior at large distances). It depends on three main factors: the angular momentum of the level, the number of nodes of the wave function, and its corresponding single particle energy. In Fig. 1, we have drawn the density distributions (fm^{-1}) of two neutrons in $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ in ^{28}O. The dotted, solid, and dashed lines are, respectively, for two neutrons in $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ levels. It is concluded again that there are neutron halos in $2s_{1/2}$ and $1d_{3/2}$ as the neutrons have an extended density distribution. The wave function for $2s_{1/2}$ slowly decayed to zero at large distance and this is why the mean-square radius in $2s_{1/2}$ is close to that in $1d_{3/2}$. The halo neutrons favor the orbit with low angular momentum and more nodes so as to enter the range with low density in which the total energy of the nucleus will increase. The total radius for a nucleus is directly related to the total wave function that depends on the occupation of levels and the wave function of the level. As the experimental two neutron separation energy for ^{24}O is as high as 6.45 MeV, in order to confirm the prediction on neutron halos in ^{24}O in the nonlinear RMF theory, we have also carried out the RMF calculation with NL1 parameters for ^{24,26,28}O. The results are given in Table III. All quantities in Table III have the same meaning and unit as those in Tables I and II. It is seen from Table III that the RMF theory with NL1 parameters also predicts that there exist neutron halos in ^{24}O. Very recently it was reported [6] that there are neutron halos in medium and heavy nuclei where the two neutron separation energies can also be compared with that in ^{24}O. It is known that NL1 parameters predict a slightly larger neutron skin than NL-SH parameters. One can see this phenomenon again. In a word, the results with NL1 and NL-SH parameters are very close even for ^{28}O and it means that the predictions in the nonlinear RMF theory are very stable. The neutron halo in ^{24}O, in the RMF theory, is related to the occupation of the $2s_{1/2}$ orbit because this is the lowest angular momentum and it has a node in its wave function.

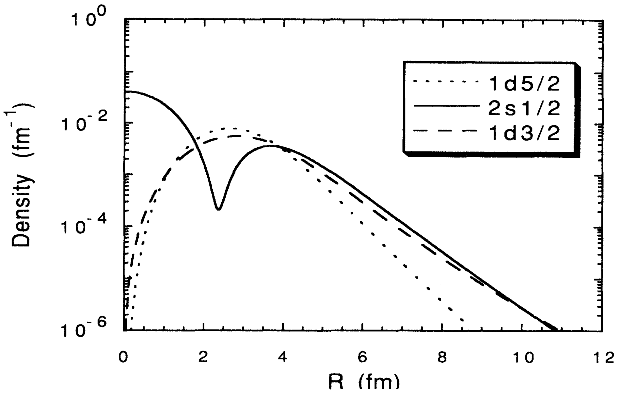

FIG. 1. The density distributions of two neutrons in $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ in ^{28}O.

It is known [34] that the RMF theory can automatically

TABLE III. The RMF results with NL1 parameters for ^{24,26,28}O. The levels of neutrons in the *s*-*d* shell and corresponding mean-square radii are given.

^AX	$\varepsilon(1d_{5/2})$	$\varepsilon(2s_{1/2})$	$\varepsilon(1d_{3/2})$	$\overline{R^2}(1d_{5/2})$	$\overline{R^2}(2s_{1/2})$	$\overline{R^2}(1d_{3/2})$	B	R_p	R_n
^{28}O	7.17	5.75	2.61	14.57	19.65	19.13	176	2.8	3.7
^{26}O	6.89	5.44	1.81	13.94	19.33	19.67	172	2.7	3.5
^{24}O	6.62	5.12		13.27	18.95		169	2.6	3.3

TABLE IV. The spin-orbit splitting Δ (MeV) between $1p_{3/2}$ and $1p_{1/2}$ for O isotopes.

Nucleus	Δ_P(NL-SH)	Δ_n(NL-SH)	Δ_p(NL1)	Δ_n(NL1)
^{28}O	5.00	4.81	4.64	4.37
^{26}O	5.77	5.58	5.54	5.45
^{24}O	6.60	6.40	6.86	6.63
^{22}O	6.16	5.85	5.91	5.61
^{20}O	6.41	6.20	5.99	5.80
^{18}O	6.63	6.55	6.05	5.98
^{16}O	6.79	6.87	6.06	6.14

give the spin-orbit splitting for a nucleus. In Table IV we give the energy of the spin-orbit splitting between $1p_{3/2}$ and $1p_{1/2}$ for O isotopes, $\Delta_{\rm LS}=\varepsilon(1p_{3/2})-\varepsilon(1p_{1/2})$ with both NL-SH and NL1 parameters. It is concluded that in the nonlinear RMF theory with NL-SH and NL1 parameters the strength of the spin-orbit splitting will decrease with the increase of neutrons for O isotopes. For ^{24}O, it is an exception and this may be related to the subshell effect of $1d_{5/2}$ or $2s_{1/2}$ and the onset of neutron halos in ^{24}O for O isotopes. For the spin-orbit splitting between $1d_{5/2}$ and $1d_{3/2}$, a similar behavior can be seen from Table II. Very recently Von-Eiff *et al.* [35], using nonlinear RMF theory, have shown that the spin-orbit splitting in asymmetric semi-infinite nuclear matter will decrease with the increase of neutron excess. Our results qualitatively agree with their conclusions. But because the spin-orbit splitting in a nucleus is a small quantity (the difference of single particle energies), and is strongly influenced by the shell and subshell effect, it is not easy to extract a general law.

We summarize the results as follows. The nonlinear relativistic mean-field theory with σ, ω, and ρ mesons and NL-SH parameters has been used for the systematic study of O isotopes. It is shown that there are neutron halos in ^{24,26,28}O. It is also found in the nonlinear RMF theory with NL-SH and NL1 parameters that the strength of the spin-orbit splitting in O isotopes will decrease with the increase of neutrons.

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