Relativistic mean-field description of a proton halo in the first excited $(1/2)^+$ state of ^{17}F

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The newly discovered proton halo in the first excited $(1/2)^+$ state of ^{17}F [R. Morlock *et al.*, Phys. Rev. Lett. **79**, 3837 (1997)] is investigated in the nonlinear relativistic mean-field model. It is shown that this model, without introducing any specifically adjusted parameters, can reproduce well not only the ground state properties of ^{17}F but also the proton halo in the excited $(1/2)^+$ state. The possibility of the existence of a proton halo in the neighboring nucleus ^{18}Ne is also discussed. [S0556-2813(98)00905-4]

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It has been well known that there exist neutron halos in light neutron-rich nuclei since the pioneering experimental work by Tanihata *et al.* [1], Mittig *et al.* [2], and Saint-Laurent *et al.* [3,4]. However, one has questioned for many years whether proton halos in light proton-rich nuclei can or do exist. A very recent experiment performed by Morlock *et al.* [5] provides a definite answer to this question and shows the existence of proton halos. They observed in a proton-capture reaction on ^{16}O at low energies, i.e., $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$, the low-energy S factor is dominated by a transition to the first $(1/2)^+$ in ^{17}F. They found the S factor increases strongly with decreasing incident energies and this indicates the existence of a proton halo in the excited state $(1/2)^+$ in ^{17}F. The root-mean-square radius of the halo proton in the bound $(1/2)^+$ state is as large as 5.3 fm [5] while the root-mean-square radius of the ^{16}O core is approximately 2.6 fm.

Theoretically various models have been applied for the investigations of neutron halos in neutron-rich nuclei [6–13] and they have explained successfully the appearance of neutron halos in these nuclei. Nevertheless, there is no model calculation on the proton halo in the excited $(1/2)^+$ state of ^{17}F as far as we know. Here we will report a nonlinear relativistic mean-field (RMF) calculation on this newly discovered proton-halo nucleus ^{17}F and its neighboring nuclei ^{16}O and ^{18}Ne. In the RMF model, the spin degrees of freedom of nucleons are treated microscopically and the spin-orbit splitting is given automatically, since it is essentially a relativistic effect. This avoids the introduction of an *ad hoc* spin-orbit potential, an advantage especially in exotic nuclei where their spin-orbit splittings are unknown.

The nonlinear relativistic mean-field theory has produced very reliable results for both even-even and odd-A nuclei throughout the Periodic Table in past years [14–24]. Especially these RMF calculations have shown that the RMF models can reproduce isotope shifts of root-mean-square radii of nuclear charge distributions in medium and heavy nuclei very well. This indicates that the model can provide us with a reliable description of proton distributions and probably also proton halos.

The RMF theory with σ, ω and ρ mesons is in the meantime a standard approach. We therefore describe here only briefly the theory. (Details can be found in Refs. [14–24].) In the RMF approach, we start from the local Lagrangian density [14–24] for interacting nucleons, σ, ω, and ρ mesons and photons,

$$\begin{aligned}\mathcal{L}=&\bar{\Psi}(i\gamma^\mu\partial_\mu-M)\Psi-g_\sigma\bar{\Psi}\sigma\Psi-g_\omega\bar{\Psi}\gamma^\mu\omega_\mu\Psi\\&-g_\rho\bar{\Psi}\gamma^\mu\rho^a_\mu\tau^a\Psi+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma-\frac{1}{2}m_\sigma^2\sigma^2-\frac{1}{3}g_2\sigma^3\\&-\frac{1}{4}g_3\sigma^4-\frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu}+\frac{1}{2}m_\omega^2\omega^\mu\omega_\mu-\frac{1}{4}R^{a\mu\nu}\cdot R^a_{\mu\nu}\\&+\frac{1}{2}m_\rho^2\rho^{a\mu}\cdot\rho^a_\mu-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}-e\bar{\Psi}\gamma^\mu A^\mu\frac{1}{2}(1-\tau^3)\Psi,\end{aligned}\tag{1}$$

with

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

$$R^{a\mu\nu}=\partial^\mu\rho^{a\nu}-\partial^\nu\rho^{a\mu},\tag{3}$$

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

The meson fields are denoted by σ, ω_μ, and ρ^a_μ and their masses are given by m_σ, m_ω, and m_ρ, respectively. The nucleon fields and rest masses 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 coupling constants between mesons and nucleons are, respectively, g_σ, g_ω, and g_ρ. g_2 and g_3 are the nonlinear couplings of the σ meson. The isospin Pauli matrices are written as τ^a with τ^3 being the third component of τ^a. We solve the nuclear many-body problem of a nucleus starting from the above Lagrangian [14–24]. Under the mean-field approximation, the mesons fields are considered as classical fields and they are replaced by their expectation values in vacuum [14–24]. Using procedures similar to those of Refs. [14,16,18,24], we obtain a set of coupled equations for mesons, nucleons, and photons. They are solved consistently in coordinate space by iteration. After the final solutions are obtained, the total binding energy of a nucleus and other quantities can be calculated from wave functions.

The parameters of the above Lagrangian density (1), such as meson masses and coupling constants are obtained by

TABLE I. The RMF results of ^{16}O and ^{17}F with NLZ.

	^{16}O	^{17}F$(1d_{5/2})$	^{17}F$(2s_{1/2})$
B (expt.) (MeV)	127.62	128.22	
B (theor.) (MeV)	127.43	128.89	127.63
R_m (fm)	2.65	2.73	2.85
R_p (fm)	2.67	2.81	3.03
R_n (fm)	2.64	2.64	2.64
R_c (fm)	2.79	2.92	3.13
$R(1d_{5/2})$ (fm)		3.66	
$R(2s_{1/2})$ (fm)			4.97
$\epsilon(1s_{1/2})(p)$	-35.70	-35.48	-35.69
$\epsilon(1p_{3/2})(p)$	-17.18	-17.01	-17.03
$\epsilon(1p_{1/2})(p)$	-11.41	-11.38	-10.90
$\epsilon(1d_{5/2})(p)$		-1.54	
$\epsilon(2s_{1/2})(p)$			-0.40
$\epsilon(1s_{1/2})(n)$	-39.74	-41.42	-41.40
$\epsilon(1p_{3/2})(n)$	-20.94	-22.82	-21.92
$\epsilon(1p_{1/2})(n)$	-15.10	-17.06	-15.71

fitting experimental observables like nuclear matter properties and binding energies and radii of a few selected spherical nuclei [16,24]. In this paper we will carry out RMF calculations of the nuclei ^{16}O, ^{17}F, and ^{18}Ne with two sets of parameters NLZ [24] and NL1 [16,24] which are frequently used by many groups. A detailed correction of the center-of-mass motion is included for the NLZ [24] and we expect that this is then a good description of bulk properties of light nuclei.

The numerical results of ^{16}O and ^{17}F with NLZ and NL1 are listed in Tables I and II, respectively. The results of ^{17}F are obtained in the following way. At first, we assume the last proton occupies the $1d_{5/2}$ level and obtain so the results for the ground state of ^{17}F. Then we assume the last proton occupies the $2s_{1/2}$ level and obtain the result for the excited $(1/2)^+$ state. In the tables, the experimental and theoretical binding energies B (MeV) and the root-mean-square (rms)

TABLE II. The RMF results of ^{16}O and ^{17}F with NL1.

	^{16}O	^{17}F$(1d_{5/2})$	^{17}F$(2s_{1/2})$
B (expt.) (MeV)	127.62	128.22	
B (theor.) (MeV)	127.30	128.62	127.34
R_m (fm)	2.65	2.72	2.86
R_p (fm)	2.66	2.80	3.03
R_n (fm)	2.64	2.64	2.64
R_c (fm)	2.78	2.92	3.13
$R(1d_{5/2})$ (fm)		3.66	
$R(2s_{1/2})$ (fm)			5.01
$\epsilon(1s_{1/2})(p)$	-36.17	-35.97	-36.06
$\epsilon(1p_{3/2})(p)$	-17.31	-17.13	-17.13
$\epsilon(1p_{1/2})(p)$	-11.26	-11.20	-10.74
$\epsilon(1d_{5/2})(p)$		-1.50	
$\epsilon(2s_{1/2})(p)$			-0.34
$\epsilon(1s_{1/2})(n)$	-40.20	-41.99	-41.80
$\epsilon(1p_{3/2})(n)$	-21.07	-23.03	-22.05
$\epsilon(1p_{1/2})(n)$	-14.94	-16.96	-15.57

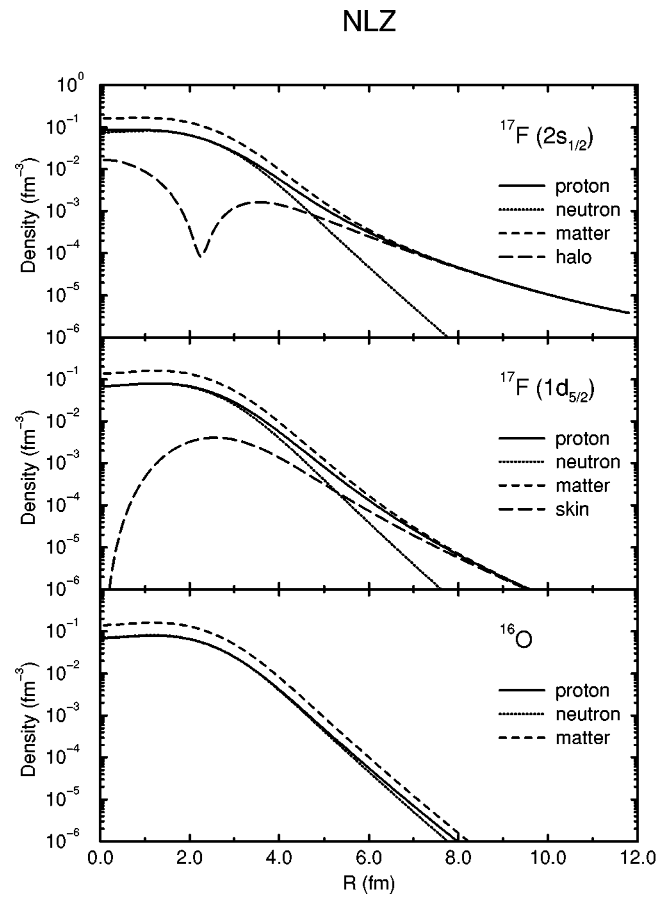

FIG. 1. The density distributions of proton, neutron, and matter in ^{16}O and ^{17}F, and of the last proton in ^{17}F$(1d_{5/2})$ and ^{17}F$(2s_{1/2})$ in the RMF theory with the NLZ force. Solid, dotted, short-dashed, and long-dashed curves represent the density distributions of proton, neutron, matter, and the last proton, respectively.

radii of matter, proton, neutron, and charge density distributions, R_m (fm), R_p (fm), R_n (fm), and R_c (fm) are given [25]. In order to elucidate whether there exists a proton skin and a halo in ^{17}F, we have also listed the single particle energy ϵ (MeV) and the root-mean-square (rms) radii of protons in the $1d_{5/2}$ and $2s_{1/2}$ levels, R $(1d_{5/2})$ (fm) and R $(2s_{1/2})$ (fm). It is seen from Table I that the differences of theoretical binding energies with NLZ and experimental ones are approximately 0.2 MeV and 0.7 MeV for ^{16}O and ^{17}F, respectively. The calculated binding energy is only 0.5% off. The RMF theory with NLZ shows that ^{17}F is stable to proton emissions no matter if the valence proton occupies the $1d_{5/2}$ or the $2s_{1/2}$ level, since in RMF the total binding energy of ^{17}F is larger than that of ^{16}O. This also agrees with the experimental fact [25,26]. The experimental RMF radii of the charge and neutron density distribution are 2.73 fm and 2.58 fm for ^{16}O [27], respectively. These values are very close to our theoretical results 2.79 and 2.64 fm.

In Table I we will see that the last proton in the levels $1d_{5/2}$ and $2s_{1/2}$ level is only weakly bound and this produces a proton skin and for $2s_{1/2}$ even a halo. We list the rms radii of the last proton in the $1d_{5/2}$ or $2s_{1/2}$ state in the eighth and ninth row. Because R $(2s_{1/2})\approx 5$ (fm) is approximately twice the matter rms radius of the core ^{16}O $R_m\approx 2.65$ fm, one can speak of a proton halo when the last proton occupies the excited $2s_{1/2}$ level. In the ground state of ^{17}F, the last

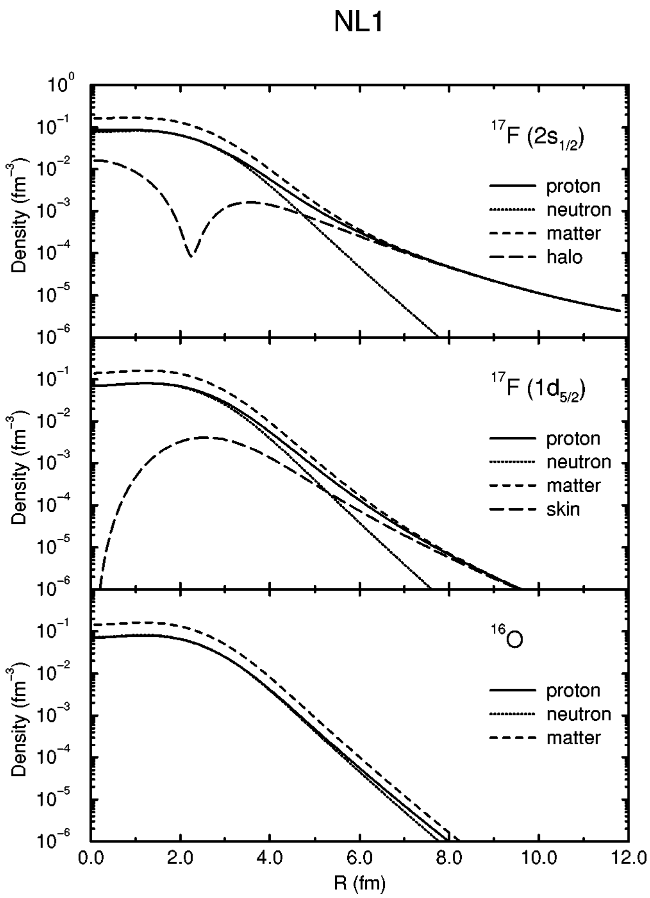

FIG. 2. Same as Fig. 1 but for the force NL1.

proton in the $1d_{5/2}$ level forms a proton skin because its rms radius is about 3.7 fm. Now let us compare our theoretical radii $R(2s_{1/2})$ and $R(1d_{5/2})$ in Table I with the corresponding experimental data from Morlock *et al.* [5]. They obtained $r_{\rm rms}(5/2^+)=3.698$ fm and $r_{\rm rms}(1/2^+)=5.333$ fm. It is seen again that our theoretical results are very close to the experimental data.

From Table II we conclude that the RMF results with NL1 also agree well with the experimental data both for binding energies and radii. Especially the experimental radii $r_{\rm rms}(5/2^+)$ and $r_{\rm rms}(1/2)^+$ from Morlock *et al.* [5] can be reproduced by the RMF model without adjusting any parameters of the Lagrangian (1). As we compare the RMF results of NL1 (Table II) with RMF results of NLZ (Table I), we see that RMF results with different force parameters are practically the same and this shows the RMF results are very stable for these nuclei.

In order to present the proton skin for the $1d_{5/2}$ ground state and the proton halo for the $2s_{1/2}$ excited state of ^{17}F, we show the density distribution of protons, neutrons, and the matter in ^{16}O and ^{17}F and the distributions of the last $1d_{5/2}$ and $2s_{1/2}$ protons in ^{17}F for the forces NLZ (Fig. 1) and NL1 (Fig. 2). In the figures, solid, dotted, short-dashed, and long-dashed curves are the density distributions of protons, neutrons, matter in ^{16}O and ^{17}F, and the distribution of the last proton of ^{17}F in the levels $1d_{5/2}$ or $2s_{1/2}$, respectively. When the last proton in ^{17}F occupies the level $2s_{1/2}$, there is a proton halo in ^{17}F because the density distributions of the protons and of the matter have a long tail, which becomes the contribution of the last proton. For the ground state of ^{17}F, there is a proton skin due to the small binding energy of the last proton in the $1d_{5/2}$ state. It is seen again that the results of the RMF approach with different force parameters are very close compared to the densities in Figs. 1 and 2.

In view of the fact that RMF results agree well with experimental data of ^{16}O and ^{17}F, it is interesting to see the RMF prediction on the neighboring nucleus ^{18}Ne. Therefore we carried out RMF calculations of ^{18}Ne for three cases: (a) we assume that there is no pairing force between protons and the two protons occupy the $1d_{5/2}$ level [^{18}Ne($1d_{5/2}$)]; (b) we assume that there is no pairing force between the protons, but the last two protons occupy the $2s_{1/2}$ level [^{18}Ne($2s_{1/2}$)]; (c) we assume that there is the pairing force between the last two protons and the proton pairing gap is assumed to be $\Delta=11.2/\sqrt{A}$ MeV (^{18}Ne). For all cases the neutron pairing force is chosen to be zero because the neutron number of

TABLE III. The RMF results of ^{18}Ne with NLZ.

	^{18}Ne($1d_{5/2}$)	^{18}Ne($2s_{1/2}$)	^{18}Ne
B (expt.) (MeV)	132.14		132.14
B (theor.) (MeV)	130.27	128.03	134.34
R_m (fm)	2.80	2.99	2.84
R_p (fm)	2.92	3.23	2.99
R_n (fm)	2.64	2.64	2.64
R_c (fm)	3.03	3.33	3.10
$R(1d_{5/2})$ (fm)	3.69		3.69
$R(2s_{1/2})$ (fm)		4.81	5.00
$\epsilon(1s_{1/2})(p)$	−35.23	−36.30	−35.25(1.00)
$\epsilon(1p_{3/2})(p)$	−16.82	−16.99	−16.82(0.99)
$\epsilon(1p_{1/2})(p)$	−11.35	−10.27	−11.22(0.98)
$\epsilon(1d_{5/2})(p)$	−1.45		−1.46(0.29)
$\epsilon(2s_{1/2})(p)$		−0.64	−0.23(0.16)
$\epsilon(1s_{1/2})(n)$	−43.03	−43.86	−42.86(1.00)
$\epsilon(1p_{3/2})(n)$	−24.62	−23.10	−24.25(1.00)
$\epsilon(1p_{1/2})(n)$	−18.97	−16.24	−18.51(1.00)

TABLE IV. The RMF results of ^{18}Ne with NL1.

	^{18}Ne($1d_{5/2}$)	^{18}Ne($2s_{1/2}$)	^{18}Ne
B (expt.) (MeV)	132.14		132.14
B (theor.) (MeV)	129.82	127.52	133.90
R_m (fm)	2.79	3.00	2.84
R_p (fm)	2.91	3.26	2.99
R_n (fm)	2.63	2.65	2.63
R_c (fm)	3.02	3.36	3.10
$R(1d_{5/2})$ (fm)	3.69		3.69
$R(2s_{1/2})$ (fm)		4.90	5.12
$\epsilon(1s_{1/2})(p)$	−35.75	−36.35	−35.76(1.00)
$\epsilon(1p_{3/2})(p)$	−16.93	−17.01	−16.93(0.99)
$\epsilon(1p_{1/2})(p)$	−11.14	−10.16	−11.02(0.98)
$\epsilon(1d_{5/2})(p)$	−1.38		−1.39(0.29)
$\epsilon(2s_{1/2})(p)$		−0.48	−0.15(0.16)
$\epsilon(1s_{1/2})(n)$	−43.71	−43.90	−43.51(1.00)
$\epsilon(1p_{3/2})(n)$	−24.91	−23.15	−24.52(1.00)
$\epsilon(1p_{1/2})(n)$	−18.92	−16.16	−18.44(1.00)

^{18}Ne is a magic number. The BCS treatment is used for case (c) and only bound levels of protons are included in the calculation. The RMF results with NLZ and NL1 are listed in Tables III and IV, respectively, where the second and third columns correspond to cases (a) and (b) and the last column corresponds to case (c). Here all quantities have a similar meaning to those in Table I and the quantity in brackets in the last column is the occupation probability of a nucleon in the corresponding single particle levels [the nucleon number in a j level is occupying weight $\times(2j+1)$].

It is seen from Tables III and IV that without proton pairing forces ^{18}Ne is stable against proton emission if the two protons occupy the $1d_{5/2}$ or $2s_{1/2}$ levels because the theoretical binding energy of ^{18}Ne is larger than that of ^{16}O. This agrees with the experimental facts [25,26]. If there is no proton pairing force, there is a proton skin in the ground state ($d^2_{5/2}$) of ^{18}Ne and there is a two-proton halo in the excited state ($s^2_{1/2}$) of ^{18}Ne because the rms radii of the protons in $1d_{5/2}$ and $2s_{1/2}$ are $R(1d_{5/2})=3.69$ fm and $R(2s_{1/2})=4.81$ fm, respectively. With proton pairing one has a certain component of a proton halo in the ground state of ^{18}Ne due to configuration mixing and a large component of a proton halo in the excited state.

In summary, we have calculated the properties of the nuclei ^{16}O, ^{17}F, and ^{18}Ne using the nonlinear RMF (relativistic mean field) model with NLZ and NL1 force parameters. The theoretical results agree well with the experimental data for binding energies and radii of these nuclei. An experimental proton halo in the first excited $(1/2)^+$ state in ^{17}F and a proton skin in the ground state of ^{17}F [5] can be reproduced by the RMF model without readjustment of any force parameters. The RMF model also predicts that there are proton halos in ^{18}Ne. After a proton halo has been discovered in ^{17}F by Morlock *et al.* [5], it will be interesting to see if there are proton halos in other nuclei and to explore their influences on various nuclear processes.

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