One-proton halo in ^{26}P and two-proton halo in ^{27}S

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Proton-drip-line nuclei ^{26}P and ^{27}S are studied in the nonlinear relativistic mean-field theory. Calculations show that the mean-square radius of protons in the $2s_{1/2}$ state is approximately 18–20 fm^2 which is abnormally large as compared with the mean-square radii of proton, neutron, and matter distributions, giving a strong evidence for proton halos in ^{26}P and ^{27}S. This indicates that the size of proton halos is as large as that of neutron halos although there exists the Coulomb barrier in proton-drip-line nuclei.

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Neutron halos have been clearly studied both experimentally and theoretically in recent years [1–11]. However, studies on proton halos are very rare. Although the proton separation energy in some light nuclei such as ^{8}B and ^{17}F is very low, there is no clear evidence for proton halos [1,12,13]. In order to understand why there is no proton halo in the above nuclei we would like to review neutron halos in ^{11}Li, ^{11}Be, and ^{14}Be. Previous studies on neutron halos [5–10] have shown that the appearance of neutron halos in them is from two main factors, the low neutron separation energy and the abnormal occupation of outside neutrons in the $2s_{1/2}$ state. The microscopic mechanism lies in the saturation to bind neutrons for neutron-drip-line nuclei [10]. The newest experimental result [14] provides us with further support on these. It is reported [14] that there is a one-neutron halo in ^{19}C due to the abnormal occupation of the last neutron in the $2s_{1/2}$ state and there is no neutron halo in ^{17}C due to the occupation of the last neutron in the $1d_{5/2}$ state. A possible cause is that the centrifugal barrier in the $1d_{5/2}$ state hindered the formation of neutron halos in a certain way. Therefore it is reasonable to choose some proton-drip-line nuclei with both low proton separation energy and outer protons in the $2s_{1/2}$ state as the candidates of proton halo nuclei. The stable nuclei ^{26}P and ^{27}S are just nuclei satisfying the above conditions as the last one proton in ^{26}P and last two protons in ^{27}S occupy the $2s_{1/2}$ state according to the shell model. In this paper we will perform the nonlinear relativistic mean-field (RMF) calculation for them.

The nonlinear relativistic mean-field (RMF) theory has produced very reliable results of nuclei throughout the periodic table in past years [15–17]. Furnstahl and Price [18] have investigated magnetic moments of some nuclei by the RMF theory. Marcos, Van Giai, and Savushkin [19] have given Coulomb displacement energies in mirror nuclei. Patra [20] has carried out the calculation on light nuclei. Warrier and Gambhir [21] have systematically calculated the single particle spectrum and spin-orbit splittings of odd-*A* systems and analyzed the effect of time reversal breaking. They have concluded [21] that the RMF results with and without time reversal invariance are practically identical and people can solve the RMF equations of odd-*A* systems with time reversal invariance if the binding energy, matter root-mean-square (RMS) radii, and single particle spectrums are only concerned. Therefore in this paper we will calculate the ground-state properties of nuclei ^{25}Si, ^{26}P, and ^{27}S in the nonlinear RMF theory with time reversal invariance. Tanihata *et al.* [22] have analyzed the stability of nuclei near the drip line and concluded that all drip-line nuclei should be spherical.

Because the nonlinear RMF theory with σ, ω, and ρ mesons is a standard theory and detailed derivations can be found in Refs. [15–24], here we briefly describe the framework of the theory. In the RMF approach we start from the local Lagrangian density [15–24]

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

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}. g_2 and g_3 are the nonlinear coupling strengths of the σ meson. The isospin Pauli matrices are written as τ^a, τ^3 being the third component of τ^a. The third term in Eq. (3) is the strength tensor of the ρ field which is usually present only in gauge theories. Since the ρ field gives a small effect, it presumably has little consequence for the calculations. In practice the above parameters such as meson masses and coupling strengths are obtained

TABLE I. The RMF results with NL-SH.

	^{25}Si	^{26}P	^{27}S
B (MeV)	182.22	182.95	183.68
R (fm)	2.88	2.98	3.06
R_p (fm)	2.97	3.11	3.23
R_n (fm)	2.77	2.78	2.80
$\overline{R^2}$ $(2s_{1/2})$ (fm^2)		19.60	19.65
$-\epsilon(1s_{1/2})(p)$	42.76	42.04	41.38
$-\epsilon(1p_{3/2})(p)$	23.80	23.38	22.98
$-\epsilon(1p_{1/2})(p)$	18.24	17.49	16.78
$-\epsilon(1d_{5/2})(p)$	6.23	6.08	5.93
$-\epsilon(2s_{1/2})(p)$		0.86	0.86
$-\epsilon(1s_{1/2})(n)$	53.57	54.36	55.20
$-\epsilon(1p_{3/2})(n)$	34.63	35.22	35.80
$-\epsilon(1p_{1/2})(n)$	28.94	29.25	29.55
$-\epsilon(1d_{5/2})(n)$	16.22	16.98	17.72

TABLE III. The RMF results with NLZ.

	^{25}Si	^{26}P	^{27}S
B (MeV)	180.99	183.27	185.72
R (fm)	2.93	3.01	3.07
R_p (fm)	3.03	3.15	3.24
R_n (fm)	2.80	2.81	2.81
$\overline{R^2}$ $(2s_{1/2})$(fm^2)		18.06	17.83
$-\epsilon(1s_{1/2})(p)$	42.63	42.46	43.18
$-\epsilon(1p_{3/2})(p)$	22.88	22.55	22.43
$-\epsilon(1p_{1/2})(p)$	17.03	16.12	15.10
$-\epsilon(1d_{5/2})(p)$	5.85	5.63	5.40
$-\epsilon(2s_{1/2})(p)$		2.40	2.69
$-\epsilon(1s_{1/2})(n)$	53.67	55.33	57.99
$-\epsilon(1p_{3/2})(n)$	34.03	34.91	36.08
$-\epsilon(1p_{1/2})(n)$	28.01	28.35	28.57
$-\epsilon(1d_{5/2})(n)$	16.12	17.00	17.93

through the fitting of the experimental observables which includes nuclear matter properties and binding energies and radii of a few selected spherical nuclei [15–24]. We will carry out numerical calculations with three sets of force parameters: NL-SH [23], NL1 [16,24], and NLZ [24].

The numerical results of ^{25}Si, ^{26}P, and ^{27}S with NL-SH, NL1, and NLZ are, respectively, listed in Tables I, II, and III. In the tables, 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 elucidate whether there exist proton halos in the above nuclei we have also listed the single particle energy $-\epsilon$ (MeV), and the mean-square radius of protons in the $2s_{1/2}$ level $\overline{R^2}$ $(2s_{1/2})$ (fm^2). The experimental binding energies of ^{25}Si, ^{26}P, and ^{27}S are, respectively, 187.00 MeV, 187.15 MeV, and 187.90 MeV [25,26]. It is seen from Table I that the difference of the theoretical binding energy with NL-SH and experimental one is approximately 4 MeV. The calculated binding energy is only 3% off. The RMF theory with NL-SH shows that ^{26}P and ^{27}S are stable to proton emissions and this agrees with the experimental fact [26,27]. As we see the single particle

TABLE II. The RMF results with NL1.

	^{25}Si	^{26}P	^{27}S
B (MeV)	180.34	182.44	184.60
R (fm)	2.93	3.01	3.08
R_p (fm)	3.03	3.15	3.25
R_n (fm)	2.80	2.81	2.82
$\overline{R^2}$ $(2s_{1/2})$(fm^2)		18.27	18.21
$-\epsilon(1s_{1/2})(p)$	43.27	42.88	43.00
$-\epsilon(1p_{3/2})(p)$	23.12	22.71	22.43
$-\epsilon(1p_{1/2})(p)$	16.95	16.03	15.07
$-\epsilon(1d_{5/2})(p)$	5.85	5.61	5.37
$-\epsilon(2s_{1/2})(p)$		2.24	2.38
$-\epsilon(1s_{1/2})(n)$	54.55	56.03	58.06
$-\epsilon(1p_{3/2})(n)$	34.54	35.37	36.34
$-\epsilon(1p_{1/2})(n)$	28.19	28.54	28.82
$-\epsilon(1d_{5/2})(n)$	16.38	17.27	18.17

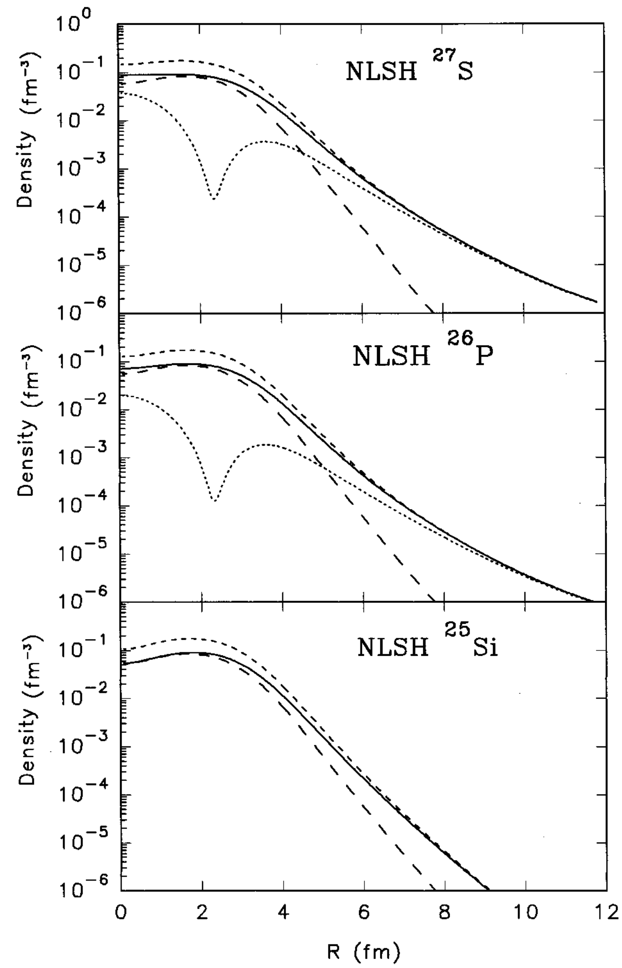

FIG. 1. The density distributions of proton, neutron, matter, and halo proton of nuclei ^{25}Si, ^{26}P, and ^{27}S in the RMF theory with NL-SH force parameters. Solid, long-dashed, short-dashed, and dotted curves are, respectively, the density distributions of proton, neutron, matter, and halo proton.

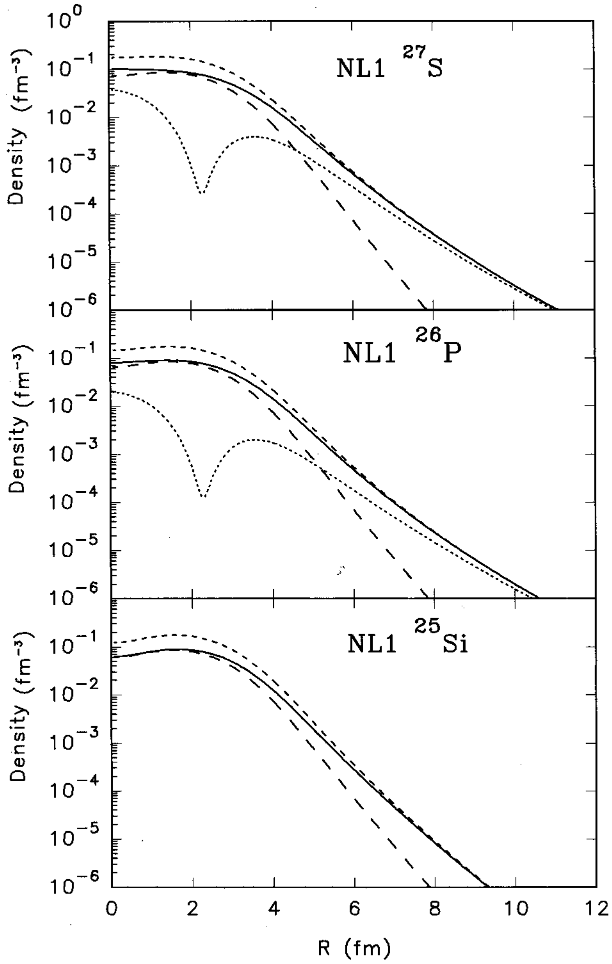

FIG. 2. Same as Fig. 1 but for NL1.

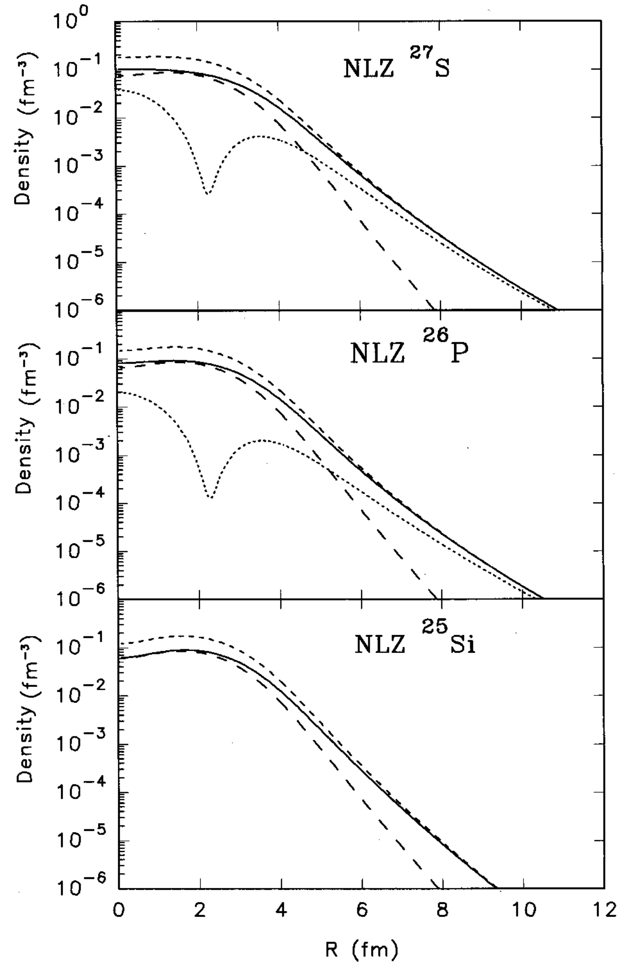

FIG. 3. Same as Fig. 1 but for NLZ.

energy we find that protons in the $2s_{1/2}$ level are weakly bound and it is possible to appear as the proton halo. Therefore we list the mean-square radius of protons in the $2s_{1/2}$ state $\overline{R^2}$ $(2s_{1/2})$ in the fifth row. Because $\overline{R^2}(2s_{1/2})\approx 20$ (fm^2) is large as compared with the mean-square radius of all protons $R_p^2\approx 10$ we conclude that there is a one-proton halo in ^{26}P and a two-proton halo in ^{27}S. It is known from the previous studies on neutron halos [5–11] that the mean-square radius of halo neutrons in ^{11}Li and ^{14}Be is also approximately 20 fm^2. This indicates that the size of proton halos is as large as that of neutron halos.

It is concluded from Tables II and III that the RMF theory with force parameters NL1 and NLZ also predicts a one-proton halo in ^{26}P and a two-proton halo in ^{27}S. The RMF theory with NL1 and NLZ still underestimates the experimental binding energy with a few MeV for the above nuclei. As we compare the RMF results in Tables I, II, and III together we find the RMF results with different force parameters are very close for both binding energies and RMS radii. This shows the RMF theory is very stable for nuclei near the proton-drip line. The change in binding energies among the three nuclei seems distinctly better with NL-SH than with NL1 and NLZ. Although the RMF theory underestimates the experimental binding energy by a few MeV, we consider its results are reliable because the underestimation is common for the above nuclei. The RMF theory with different force parameters shows that ^{26}P and ^{27}S are stable to proton emissions and there exist proton halos in ^{26}P and ^{27}S. So we consider the underestimation will have some influence on the total RMS radii and it will not have significant influence on the proton halo. This means the conclusions on the one-proton halo in ^{26}P and two-proton halos in ^{27}S will be true.

In Figs. 1–3, we have drawn the density distribution (fm^{-3}) of proton, neutron, matter, and halo proton in ^{25}Si, ^{26}P and ^{27}S. In the figures, solid, long-dashed, short-dashed, and dotted curves are, respectively, the density distributions of proton, neutron, matter, and halo proton. It is evident that there are proton halos in ^{26}P and ^{27}S as their density distribution of protons have a long tail. But we also notice that ^{25}Si has a proton skin due to the weak binding of six protons in the $1d_{5/2}$ state.

In conclusion, we have calculated the ground-state properties of ^{25}Si, ^{26}P, and ^{27}S using the nonlinear RMF theory with NL-SH, NL1, and NLZ force parameters. It is shown that protons in the $2s_{1/2}$ state in ^{26}P and ^{27}S are weakly bound and form proton halos. The size of proton halos in them is as large as that of neutron halos near the neutron-drip line. If the proton halo is verified, it will lead to new phenomena in nuclear reactions because it is a charged halo. In the future one can investigate the influence of the proton halo on some new decay modes such as β^+-delayed proton emissions or direct proton emissions in excited states in proton-halo nuclei. It is also possible to explore the proton halo by the Coulomb excitation, proton-scattering and electron-scattering experiments.

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