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Halo or Skin in the Excited States of Two Couples of Mirror Nuclei ^{13}N-^{13}C and ^{15}N-^{15}O*

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Abstract: Properties of two pairs of mirror nuclei ^{13}N-^{13}C and ^{15}N-^{15}O are investigated by using the nonlinear relativistic mean-field theory. It is found that all the calculated binding energies with two different parameter sets are very close to the experimental ones for both the ground states and the excited states. The calculations show that the first excited state ($2s_{1/2}$) and the third excited state ($1d_{5/2}$) in ^{13}N are both unbound resonances with proton halo structure, whereas the third excited state ($1d_{5/2}$) in ^{13}C is weakly bound with a neutron skin. It is also predicted that there has a proton halo in the second excited state ($2s_{1/2}$) of ^{15}N as well as a neutron skin in the first excited state ($2s_{1/2}$) of ^{15}O.

Key words: mirror nuclei; excited state; relativistic mean field; halo (skin)

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The nuclei far from the β-stability line have been studied widely and exotic structures (halos or skins) in the ground states were found in many nuclei[1－22]. However, studies on halo or skin in the excited states of nuclei near the β-stability line are relatively scarce. Morlock et al[23] shed light on the existence of proton halo in the excited states of stable nuclei firstly. They revealed experimentally the existence of a proton halo in the first excited state of ^{17}F. Ren et al[24] investigated ^{17}F using the nonlinear relativistic mean-field (RMF) theory and reached the same conclusion. Liu et al[25] and Lin et al[26] showed the existence of neutron halo in the excited states of nuclei ^{12}B and ^{13}C. Ren et al[27] calculated nucleon density distributions for the excited states of ^{13}C, ^{12}B, ^{16}N and ^{17}O with RMF and gave a theoretical proof for halo and skin. Moreover, Arai et al[28] investigated the more complicated halos in the second excited state of ^{6}Li with a fully microscopic three-cluster model and predicted that ^{6}Li has a conspicuous halo-like structure formed by a neutron and a proton surrounding the α core, i.e., deuterium halos. Li et al[29] provided the experimental evidence of deuterium halos in the second excited state of ^{6}Li.

Since RMF theory has been applied with con-

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siderable success to the quantitative description of nuclear properties in the ground states and to the prediction for the halo in the excited states[2,5,8,24,27,30—36]), it is also interesting to give theoretical prediction for halo or skin in the excited states of other nuclei with RMF model. In this paper, we investigate existance of a halo or a skin in some excited states of two couples of mirror nuclei ^{13}N-^{13}C and ^{15}N-^{15}O using the frame of nonlinear RMF.

The RMF theory with σ, ω, and ρ meson is in the mean time a standard approach. Here we make a brief description (Details can be found in Refs. [2, 5, 8, 30—36]). We start from the local Lagrangian density for interacting nucleons, σ, ω, and ρ mesons and photons, which are used to obtain the RMF equations.

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

with

$$\begin{aligned}\Omega^{\mu\nu} &= \partial^{\mu}\omega^{\nu} - \partial^{\nu}\omega^{\mu}, \\ R^{a\mu\nu} &= \partial^{\mu}\rho^{a\nu} - \partial^{\nu}\rho^{a\mu}, \\ F^{\mu\nu} &= \partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu},\end{aligned}$$

where σ, ω_{μ}, and ρ^{a}_{μ} denote the meson fields 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, respectively. A is the photon field which is responsible for the electromagnetic interaction. The effective coupling constants between mesons and nucleons are g_{σ}, g_{ω}, and g_{ρ}, respectively. The coupling constants of the nonlinear σ terms are called g_2 and g_3. τ^{a} represents the isospin Pauli matrices and τ^{3} is 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. Using the procedures similar to those of Refs. [2, 5, 31, 33], we obtain a set of coupled equations for mesons, nucleons, and photons. They are solved consistently in coordinate space by iteration. The nonlinear RMF parameter sets of NL3[37] is chosen for numerical calculations in this work. We use the term $0.75 \times 41\ A^{1/3}$ to evaluate the correction of the additional energy due to the motion of the center of mass[6].

We select ^{13}C as an example to explain the details of the calculations. First, we calculate the binding energy, single-particle levels, RMS radii of proton and neutron density distributions for the ground state of the core nucleus (^{12}C). Then we calculate the ground state properties of ^{13}C by assuming the last neutron occupies the state $1p_{1/2}$. Finally the properties for the first or the third excited states of ^{13}C are obtained by assuming the last neutron occupies $2s_{1/2}$ or $1d_{5/2}$. Every step is a self-consistent RMF calculation. The total binding energy, separation energy, single particle energy, radii, and wave functions of each nucleon are obtained and root-mean-square radius of the last proton can be calculated by its wave function.

The calculated results for the mirror partners ^{13}N-^{13}C are displayed in table 1 and those for ^{15}N-^{15}O are listed in table 2. In the two tables, nL_J (LP) denotes the quantum number of the state occupied by the last nucleon. $B_{\exp}$[38] and B represent experimental and theoretical binding energies, respectively. The root-mean-square (RMS) radii of matter, proton, neutron, and the last nucleon density distributions are denoted by R_{m}, R_{p}, R_{n}, R_{LP}, respectively. The single particle energy of the last nucleon (a proton for ^{13}N and ^{15}N or a neutron for ^{13}C and ^{15}O) is denoted by $\varepsilon_{\mathrm{LP}}(\mathrm{p/n})$.

It can be seen that the RMF calculations can reproduce the binding energies well as a whole. The differences of binding energy between theory and experiment are very small. It indicates that the theoretical binding energies are very close to the experimental ones. One should note that all these results are obtained without readjustment of any parameter.

Table 1 The RMF results for ^{13}N-^{13}C with NL3*

	^{13}N			^{13}C		
nL_J(LP)	$1p_{1/2}^{GS}$	$2s_{1/2}^{ES1}$	$1d_{5/2}^{ES3}$	$1p_{1/2}^{GS[27]}$	$2s_{1/2}^{ES1}$	$1d_{5/2}^{ES3}$
B_{exp}	94.11	91.74	90.56	97.11	94.02	93.26
B	94.12	92.86	91.46	98.09	92.48	92.49
R_m	2.38	/	/	2.40	2.48	2.41
R_p	2.46	/	/	2.33	2.21	2.24
R_n	2.29	/	/	2.45	2.71	2.53
R_{LP}	3.13	/	/	3.03	4.71	3.88
ϵ_{LP}(p/n)	−4.76	+0.52	+2.40	−8.44	−1.93	−0.33
$\|R_p-R_n\|$	0.17	/	/	0.12	0.50	0.29

* GS, ES1 and ES3 denote the ground states, the first and the third excited states, respectively. The units of binding energies and of single particle energies are in MeV and those of various RMS radii and the corresponding differences between proton RMS radii and neutron RMS radii are in fm. The other details can see text.

Table 2 The RMF results for ^{15}N-^{15}O with NL3*

	^{15}N			^{15}O		
nL_J(LP)	$1p_{1/2}^{GS}$	$2s_{1/2}^{ES2}$	$1d_{5/2}^{ES2}$	$1p_{1/2}^{GS}$	$2s_{1/2}^{ES1}$	$1d_{5/2}^{ES2}$
B_{exp}	115.49	110.19	110.22	111.96	106.78	106.72
B	115.16	108.19	111.87	111.79	104.80	104.75
R_m	2.55	2.75	2.52	2.56	2.67	2.61
R_p	2.52	2.90	2.53	2.61	2.60	2.57
R_n	2.58	2.61	2.51	2.50	2.74	2.51
R_{LP}	2.87	4.79	3.47	2.83	4.30	3.38
ϵ_{LP}(p/n)	−11.22	−0.88	−1.25	−14.59	−3.58	−4.12
$\|R_p-R_n\|$	0.06	0.29	0.02	0.11	0.14	0.06

* The other details can see the caption for table 1 and see text.

From the single particle energy of the valence proton for ^{13}N listed in table 1, we know that the two lowest excited states of ^{13}N are both unbound which are consistent with the experimental results[38, 39]. It shows that the RMF code with NL3 parameters can predict properly the unbound excited states for ^{13}N. As well known, a wave function for an unbound resonance is not square integrable and must therefore lead to an infinitely large RMS radius. So here only the binding energies are given and all kinds of radii and corresponding density distributions are both omitted. It is not easy to give a confirmed conclusion to the structure in the excited states of ^{13}N. However, considering the charge symmetry, one can say that there may exist a unbound proton halo in the first and the third excited states of ^{13}N, respectively.

The results for ^{13}C are also displayed in table 1 and Fig. 1, respectively for comparison with its mirror partner ^{13}N. Since the properties for the first excited state in ^{13}C has been calculated previously[27], here we just emphasize on the third excited state of ^{13}C. The RMS radius of the valence neutron in the third excited state of ^{13}C is 3.88 fm. It agrees with the experimental result (3.68 ± 0.40) fm within the error bar, where it was declared that there is a neutron skin in the third excited state of ^{13}C[25]. The single particle energy (−

0.33 MeV) of the valence neutron is small and it indicates that the $2s_{1/2}$ excited state is weakly bound compared with the ground state in ^{13}C[38,39].

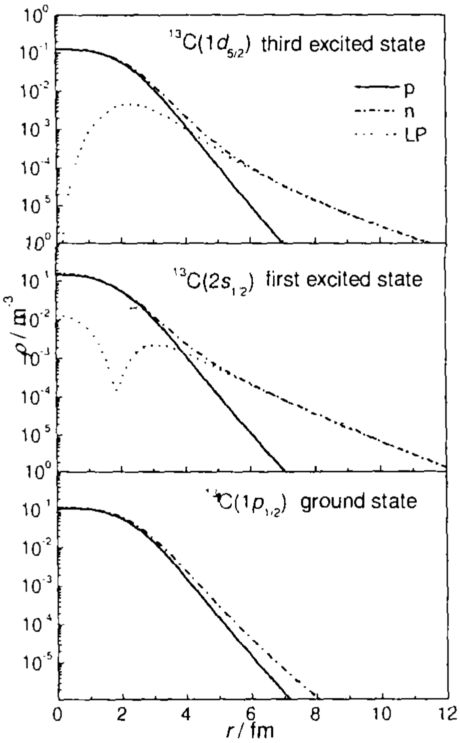

Fig. 1 The density distributions of proton, neutron, and the last nucleon for the ground state, the first and the third excited states in ^{13}C.

At the same time, it should be noted that the calculated $|R_p - R_n|$ (0.29 fm) is not very large. Therefore it suggests that, as done by Liu et al. a neutron skin can form in the third excited state of ^{13}C. From Fig. 1, it can be seen that the neutron density distribution shows an extensive region than the proton one when the last neutron occupies the $1d_{5/2}$ state. It is somewhat similar to that for the first excited state of ^{13}C where a neutron halo has been predicted both experimentally and theoretically[25,27].

For ^{15}N-^{15}O, the first and the second excited states for ^{15}N are the $1d_{5/2}$ and $2s_{1/2}$, respectively, whereas the excitation order of ^{15}O is contrary to that for ^{15}N[39]. It can be seen that from table 2, the calculated results for the first excited state ($1d_{5/2}$), are almost the same as those for the ground state, ($1p_{1/2}$) in ^{15}N, except for the smaller single particle energy of the valence proton. Hence there is no any exotic structure in the first excited state of ^{15}N. But the situation is significantly different when one sees the second excited state of ^{15}N, where the RMS radius of the last proton is 4.79 fm and it is greatly larger than the matter radius of 2.75 fm. In addition, $|R_p - R_n|$ (0.29 fm) for the second excited state is highly larger than that for the ground state where it is 0.06 fm. The single particle energies for ^{15}N listed in table 2 show that the last proton is tightly bound in the ground state (−11.22 MeV) and weakly bound in the excited state (−0.88 MeV). We plot in Fig. 2, the density distributions of proton, neutron and the last proton for ^{15}N. It can be seen that the proton density distribution for the second excited state of ^{15}N has a long tail while that for the first excited state is normal. Therefore, it suggests that there exists a proton halo in the second excited state of ^{15}N. From table 2 we can see that for the first excited state of ^{15}O, the valence neutron RMS radius is 4.30 fm, which is greatly larger than the matter RMS radius, 2.67 fm. However, the difference of RMS radius between proton and neutron for the first excited state is only 0.14 fm, which is little larger than that of the ground state, 0.11 fm, but is rare smaller than that for the second excited state of ^{15}N, 0.25 fm. Moreover, the single particle energy of the last neutron in the first excited state of ^{15}O is −3.58 MeV, and its absolute value is relatively larger than that for the second excited state of ^{15}N, −1.33 MeV. Hence it is suggested that there might exist a neutron skin in the first excited state of ^{15}O. The neutron density distribution in the first excited state of ^{15}O is obviously diffuse compared with that in the ground state (see Fig. 2), however the difference between neutron and proton density distributions is not very large and this confirms the above conclusion. There is no exotic structure in the $1d_{5/2}$ state of ^{15}O which is the same as that for the first excited state of ^{15}N.

To summarize, we calculated the properties of

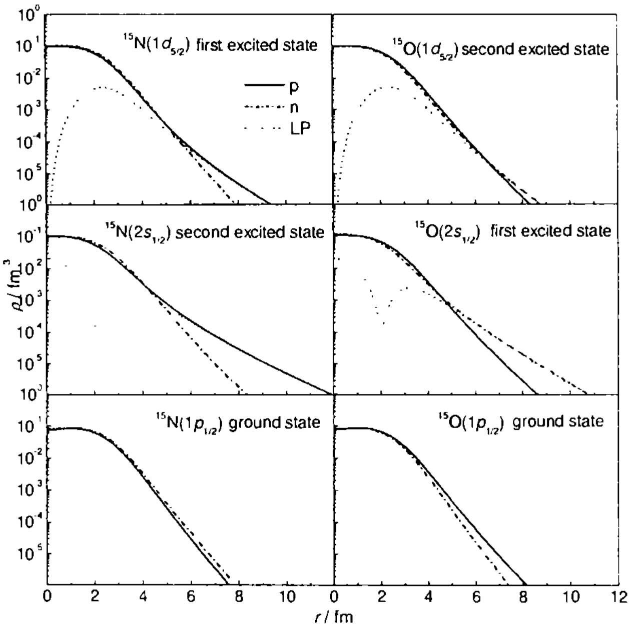

Fig. 2 The density distributions of proton, neutron, and the last nucleon for the ground state, the first and the second excited states in the mirror nuclei ^{15}N-^{15}O.

two pairs of mirror nuclei by using the framework of nonlinear RMF. It shows that the RMF code can well reproduce the experimental binding energies. The calculations show that the first and the third exited states, $2s_{1/2}$ and $1d_{5/2}$ in ^{13}N are both unbound while the third exited states, $1d_{5/2}$ in ^{13}C, together with the first excited state, $2s_{1/2}$ in ^{15}N, and the second excited state, $2s_{1/2}$ in ^{15}O are all weakly bound. The density distributions of proton for ^{15}N in the $2s_{1/2}$ state extends sharply and has a long tail, which is absolutely different from those for its ground states. It shows that there exists a proton halo in the second excited state of ^{15}N. At the same time, it is predicted that there is a neutron skin in the state of ^{13}C and in the first excited state of ^{15}O because of the smaller differences of density distributions between proton and neutron as well as the larger single particle energy of the last neutron. For ^{13}N, it is possible that there has a proton halo and skin in the first and the third unbound excited resonances, respectively. It is necessary to carry out related experiment for the confirmation of our theoretical prediction.

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镜像核$^{13}\mathrm{N}$-$^{13}\mathrm{C}$和$^{15}\mathrm{N}$-$^{15}\mathrm{O}$中的激发态晕或皮*

陈金根[1,2]，蔡翔舟[2]，沈文庆[2,4]，马余刚[2]，任中洲[3]，蒋潍舟[2]
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摘　要：用非线性相对论平均场对两对镜像核$^{13}\mathrm{N}$-$^{13}\mathrm{C}$和$^{15}\mathrm{N}$-$^{15}\mathrm{O}$进行了研究．发现无论在基态还是激发态，用两套参数所得的结合能都跟实验值很接近．计算结果显示$^{13}\mathrm{N}$的第一激发态($2s_{1/2}$)和第三激发态($1d_{5/2}$)各存在一个非束缚的质子晕，而$^{13}\mathrm{C}$的第三激发态($1d_{5/2}$)存在一个弱束缚的中子皮．另外研究表明，在另一对镜像核$^{15}\mathrm{N}$-$^{15}\mathrm{O}$的第二激发态($2s_{1/2}$)和第一激发态($2s_{1/2}$)分别存在一个中子晕和质子皮．

关 键 词：镜像核；激发态；相对论平均场；晕(皮)

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