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Coulomb effects on the formation of proton halo nuclei*

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This paper makes some qualitative and quantitative analyses about halo formation rules of some mirror nuclei with the relativistic mean-field (RMF) theory and the Woods–Saxon mean-field model. By analysing two opposite effects of Coulomb interaction on the proton halo formation, it finds that the energy level shift has a larger contribution than that of the Coulomb barrier when the mass number A is small, the hindrance of the Coulomb barrier becomes more obvious with the increase of the mass number A, and the overall effect of the Coulomb interaction almost disappears when $A \approx 39$ as its two effects counteract with each other.

Keywords: Coulomb effects, halo nuclei, relativistic mean-field theory, Woods–Saxon mean-field model

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1. Introduction

Nuclear halo is a kind of exotic structure in which the valence nucleon extends outside the binding potential because of its weakly bound character. Halo nuclei have been extensively investigated both experimentally and theoretically.[1−6] Most of the halo nuclei are confirmed as neutron halos, while proton halos observed are rather scarce. Since ^{8}B and ^{17}Ne are predicted as proton halos,[7−12] the first excited state of ^{17}F[5,13] and proton-rich isotopes P and S[4,14−17] have been predicted as proton halos and some of them have been probed experimentally. However, up to now, the investigations on the formation mechanism of proton halo nuclei are relatively insufficient.

In our previous work,[18] we investigate the exotic structures of some light mirror nuclei with the relativistic mean-field (RMF) theory and find that a proton halo occurs more easily than a neutron halo in a pair of mirror nuclei, that the difference between the root-mean-square (rms) radius of the valence nucleon in each pair of mirror nuclei becomes smaller with the increase of the mass number A, and that all the ratios of the rms radius of the valence nucleon to that of the matter in each pair of mirror nuclei decrease almost linearly with the increase of A, as shown in Fig.1. In this work, we make some qualitative and quantitative analyses on the results mentioned above with the RMF theory and the Woods–Saxon mean-field model and find that Coulomb effects are the direct cause to produce the above results.

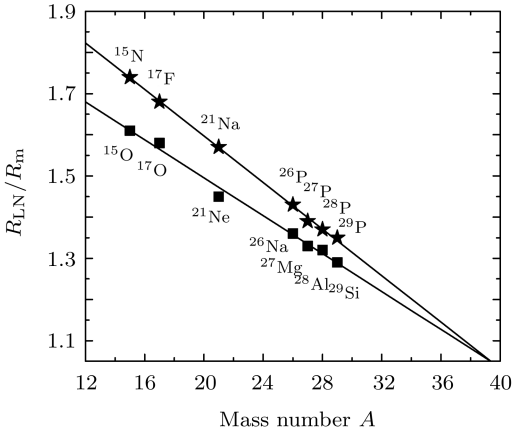


Fig.1. This figure is taken from Ref.[18]. The ratio of the rms radius of the valence nucleon to that of the matter as a function of the mass number A. The solid stars (★) stand for the nuclei with a valence proton and the solid squares (■) stand for the nuclei with a valence neutron.

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As the nuclear force is nearly independent of charge, the difference between the structures of mirror nuclei should come mainly from Coulomb interaction. Therefore, we can explore the role of Coulomb interaction on the formation of proton halo nuclei by the investigation on mirror nuclei. Coulomb interaction has two effects on the formation of proton halo nuclei. On the one hand, it makes the energy level shift closer to the Fermi level so that it is easier for the valence proton to penetrate outside the binding potential. On the other hand, the Coulomb barrier of the proton hinders the proton penetration. We make some analyses about Coulomb effects on the formation of proton halo nuclei as follows.

2. The RMF results and discussion

First, we make some qualitative analyses with the RMF theory. The RMF theory has proved to be successful for many nuclear properties.[19−31] The details of our RMF calculations can be found in Ref.[18]. We

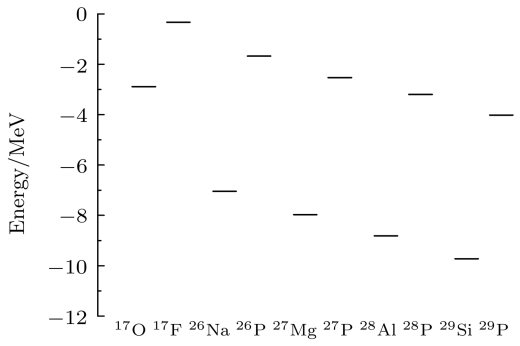


Fig.2. The single neutron energy levels of the $2s_{1/2}$ states in ^{17}O, ^{26}Na, ^{27}Mg, ^{28}Al, and ^{29}Si, and the single proton energy levels of the $2s_{1/2}$ states in ^{17}F, ^{26}P, ^{27}P, ^{28}P, and ^{29}P.

plot the single nucleon energy levels of the $2s_{1/2}$ states in the five pairs of mirror nuclei in Fig.2 and the variations of the Coulomb, the nuclear and the total potentials in ^{17}O–^{17}F and ^{29}Si–^{29}P with the radial coordinates in Fig.3. Here, the potentials are those of the valence proton in ^{17}F, ^{29}P and of the valence neutron in ^{17}O, ^{29}Si, respectively. The potentials in the other three pairs of mirror nuclei are similar to those in ^{17}O–^{17}F and ^{29}Si–^{29}P. From Fig.2 we can see that the single proton energy levels in ^{17}F, ^{26}P, ^{27}P, ^{28}P and ^{29}P are higher than the single neutron energy levels in their respective mirror nuclei, and that the energy level shift in the $2s_{1/2}$ orbits between mirror nuclei becomes larger with the increase of A. The increase of energy level shift will cause the increase of the difference between the valence nucleon dispersion of each pair of mirror nuclei. But in fact, the difference between the valence nucleon dispersion becomes smaller

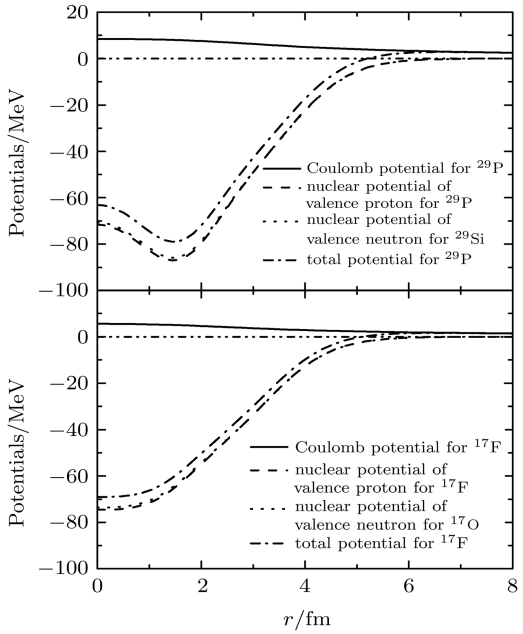


Fig.3. The variations of the mean-field potentials with the radial coordinates in ^{17}O–^{17}F and ^{29}Si–^{29}P. Solid, dashed and dash-dotted curves represent the Coulomb potential, the nuclear potential and the total potential of the valence proton in ^{17}F and ^{29}P, respectively. Dotted curve represents the nuclear potential of the valence neutron in ^{17}O and ^{29}Si.

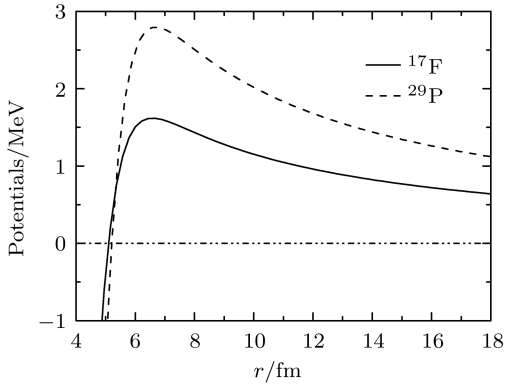


Fig.4. Coulomb barriers in ^{17}F and ^{29}P. The solid and dashed curves represent those in ^{17}F and ^{29}P, respectively.

with the increase of A. This may arise from Coulomb barrier. The Coulomb barriers in ^{26}P, ^{27}P, and ^{28}P lying in the space between those in ^{17}F and ^{29}P are not shown. From Fig.4 we can see that the height

of Coulomb barrier increases with the increase of A, which means the hindrance of Coulomb barrier becomes larger with the increase of A. Because the two opposite effects of Coulomb interaction contribute to the dispersion of the valence proton simultaneously, we can infer that the energy level shift has a larger contribution than that of Coulomb barrier when A is small, and that the hindrance of Coulomb barrier becomes more obvious with the increase of A. When $A \approx 39$ (see Fig.1), the overall effect of the Coulomb interaction almost disappears as its two effects counteract with each other.

3. The Woods–Saxon mean-field results and discussion

Next, we make some quantitative analyses with the Woods–Saxon mean-field model. In this model, the nucleus is assumed to be composed of nuclear core and valence nucleon outside the core. The normalized single-particle radial wave function $\phi_{nlj}(r)$ in the (nlj) bound state can be obtained by solving the Schrödinger equation. The potential is chosen as

$$V(r) = V_{\rm N}(r) + V_{\rm C}(r), \tag{1}$$

where the nuclear potential $V_{\rm N}(r)$ is chosen as Woods–Saxon potential

$$V_{\rm N}(r) = V_0 / \left\{1 + \exp\left(\frac{r - r_0 A^{1/3}}{a_0}\right)\right\}, \tag{2}$$

and $V_{\rm C}(r)$ is Coulomb potential. As we are dealing with the valence particle in s state whose orbital angular momentum is zero, the spin–orbit coupling term vanishes. Here, the potential depth V_0 of Woods–Saxon potential is adjusted to reproduce the separation energy of the valence nucleon. The parameters r_0 and a_0 are the radius and diffuseness parameters, respectively. In this work, r_0 and a_0 are chosen as the normal values 1.25 fm and 0.65 fm, respectively.[6,32,33]

The root-mean-square (rms) radius of the valence nucleon $R_{\rm LN}$ in the orbit (nlj) can be obtained from the single-particle radial wave function $\phi_{nlj}(r)$ by

$$R_{\rm LN} = \left[\int_0^\infty r^4 \phi_{nlj}^2(r)\,{\rm d}r\right]^{1/2}. \tag{3}$$

The results obtained with the Woods–Saxon mean-field model are listed in Table 1, where $R_{\rm i}$ denotes the increase of $R_{\rm LN}$ caused by the energy level shift, $R_{\rm d}$ denotes the decrease of $R_{\rm LN}$ caused by Coulomb barrier, $R_{\rm c}$ denotes the contribution of the overall effect of the Coulomb interaction on the dispersion of the valence proton, and $R_{\rm c} = R_{\rm i} + R_{\rm d}$. We choose ^{17}O–^{17}F as an example to explain the details of the calculations. First, we obtain the rms radii of the valence nucleons $R_{\rm LN}$ with the Woods–Saxon mean-field model (4.27 fm for ^{17}O and 5.43 fm for ^{17}F). The potential depths of ^{17}O and ^{17}F are different here. In order to examine the effect due to the shift of level energy, we temporarily shift the level energy of the valence neutron in ^{17}O up to that of the valence proton in ^{17}F, then calculate the rms radius of the valence neutron in ^{17}O. Actually, this is equivalent to switch off the Coulomb barrier of the valence proton in ^{17}F because the potential depths of ^{17}O and ^{17}F are same under this condition. The rms radius obtained under this condition is 10.95 fm. It is much larger than the actual value of ^{17}O. It implies that the energy level shift makes the rms radius increase by 6.68 fm ($R_{\rm i}$) if Coulomb barrier is neglected. However, Coulomb barrier hinders the dispersion of the valence proton. The rms radius of ^{17}F is less than the result obtained by neglecting the effect of Coulomb barrier. Therefore, Coulomb barrier makes rms radii decrease by 5.52 fm ($R_{\rm d}$). In Table 1, "–" of $R_{\rm d}$ means the decrease of $R_{\rm LN}$. The variations of $R_{\rm i}$, $R_{\rm d}$ and $R_{\rm c}$ with the mass number A are given in Fig.5. One can see from Table 1 and Fig.5 that the two effects of Coulomb interaction on the dispersion of the valence proton are opposite,

Table 1. The contributions of the energy level shift and Coulomb barrier to the formation of proton halo nuclei obtained with the Woods–Saxon mean-field model.

	^{17}O	^{17}F	^{21}Ne	^{21}Na	^{26}Na	^{26}P	^{27}Mg	^{27}P	^{28}Al	^{28}P	^{29}Si	^{29}P
$R_{\rm LN}$/fm	4.27	5.43	4.40	5.37	4.19	4.87	4.10	4.60	3.98	4.33	3.93	4.22
$R_{\rm i}$/fm		6.68		9.49		5.10		2.23		1.24		0.98
$R_{\rm d}$/fm		–5.52		–8.52		–4.42		–1.73		–0.89		–0.39
$R_{\rm c}$/fm		1.16		0.97		0.68		0.50		0.35		0.29

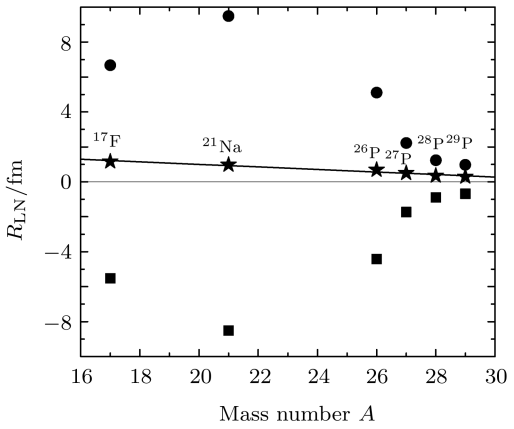


Fig.5. The contributions of the energy level shift and Coulomb barrier to the halo formation obtained with the Woods–Saxon mean-field model. The solid circles (•) represent the increase of $R_{\rm LN}$ induced by the energy level shift $R_{\rm i}$, the solid squares (■) represent the decrease of $R_{\rm LN}$ induced by Coulomb barrier $R_{\rm i}$ and the solid stars (★) represent the overall effect of the Coulomb interaction on $R_{\rm LN}$, $R_{\rm c}$.

and that the energy level shift has a larger contribution than that of Coulomb barrier when A is small. However, there is a more obvious hindrance of Coulomb barrier with the increase of A so that the overall effect of Coulomb interaction decreases almost linearly. When $A \approx 34$, the overall effect of the Coulomb interaction almost disappears as its two effects counteract with each other. These rules obtained with the Woods–Saxon mean-field model are basically in agreement with those with the RMF, although there is a small difference in mass number A in which the overall effect of the Coulomb interaction disappears. This difference may result from the difference between the two theoretical models.

4. Summary

In summary, some qualitative and quantitative analyses about halo formation rules obtained in our previous work[18] are made with the RMF theory and the Woods–Saxon mean-field model to explore the effects of Coulomb interaction on the formation of proton halo nuclei. We find: (i) the energy level shift induced by Coulomb interaction has a larger contribution than that of the Coulomb barrier when the mass number A is small; (ii) the hindrance of the Coulomb barrier becomes more obvious with the increase of A; (iii) when $A \approx 39$, the overall effect of Coulomb interaction almost disappears as its two effects counteract with each other.

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