Neutron halos in the excited states for $N = 127$ isotones

SUN Qin(孙琴)[1)] GUO Jian-You(郭建友)[2)]

(School of Physics and Material Science, Anhui University, Hefei 230039, China)

Abstract Properties of the ground states and the excited states of N=127 isotones are investigated by using the nonlinear relativistic mean field theory with the interactions PK1. By analyzing the rms of proton and neutron, the single particle energies of valence nucleon and the density distributions of neutron, proton and the last neutron, it can be found that there exists a neutron halo in the excited states of $3d5/2$, $4s1/2$ and $3d3/2$ in ^{209}Pb. It is also predicted that there exists a neutron halo in the excited states of $3d5/2$, $4s1/2$ and $3d3/2$ in ^{207}Hg, ^{208}Tl, ^{210}Bi and ^{211}Po.

Key words relativistic mean field, halo, the excited states

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1 Introduction

Since the experimental discovery of neutron halo phenomena in ^{11}Li[1],the study of exotic nuclei (halo or skin) have attracted much interest recently . However, the halo nuclei found to date are mainly limited in the light nuclear region or medium nuclear region. In order to confirm the universality of halo phenomena entirely, it is necessary to search for the neutron halo in heavy nuclei. Liu[2] have investigated the radial distributions of the last neutron in ^{209}Pb by means of an analysis of the ^{208}Pb(d,p)^{209}Pb reactions, they pointed out that there exist halo or skin structure in ^{209}Pb. In order to further check whether halo or skin structure exists in other nuclei of heavy nuclear region, we also investigate systematically for $N = 127$ isotones using the frame of nonlinear RMF theory. It is well known that RMF theory has been applied with considerable success to the quantitative description of nuclear properties in the ground states and to the prediction for the halo in the excited states, it is also interesting to give theoretical prediction for halo in the excited states of other nuclei with RMF model.

2 The RMF theory

As the relativistic mean-field (RMF) theory is a standard method for describing properties of the spherical nuclei and some deformed nuclei and its details can been found elsewhere such as Refs. [3—6], here we only describe the outline of the theory. 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.

$$\begin{aligned} L = & \overline{\psi}(\mathrm{i}\gamma^\mu\partial_\mu - M)\psi + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \\ & \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 - g_\sigma\overline{\psi}\sigma\psi - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \\ & \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}g_4(\omega_\mu\omega^\mu)^2 - g_\omega\overline{\psi}\gamma_\mu\psi\omega^\mu - \\ & \frac{1}{4}R^\alpha_{\mu\nu}R^{\alpha\mu\nu} + \frac{1}{2}m_\rho^2\rho^\alpha_\mu\rho^{\alpha\mu} - g_\rho\overline{\psi}\gamma_\mu\tau^\alpha\psi\rho^{\alpha\mu} - \\ & \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - e\overline{\psi}\gamma_\mu\frac{1-\tau_3}{2}A^\mu\psi \ . \end{aligned}$$

With

$$\begin{aligned} \Omega_{\mu\nu} &= \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \ , \\ R^\alpha_{\mu\nu} &= \partial_\mu\rho^\alpha_\nu - \partial_\nu\rho^\alpha_\mu - 2g_\rho\varepsilon^{abc}\rho^b_\mu\rho^c_\nu \ , \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \ . \end{aligned}$$

Where σ, ω_μ and ρ^α_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 $\overline{\psi}$ and M, respectively. A is the photon field which is responsible for the electromagnetic interaction. The

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1) E-mail: sunqin5432@163.com
2) E-mail: jianyou@ahu.edu.cn

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 $g2$ and $g3$. τ^α represents the isospin Pauli matrices and τ^3 is the third component of τ^α. 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. [4] and [5], we obtain a set of coupled equations for mesons, nucleons and photons. They are solved consistently in coordinate space by iteration. We use the term $0.75 \times 41A^{\frac{1}{3}}$ to evaluate the correction of the additional energy due to the motion of the center of mass. Here only one-nucleon halo is concerned, the pairing is ignored in the calculations.

3 Calculation and results

We select ^{209}Pb as an example to explain the details of the calculations. The calculated results for ^{209}Pb are listed in Table 1 in the RMF theory with the interactions PK1[7]. In Table 1 we also note that there is not a neutron halo in the ground state, Whereas the situations in the excited states of $3d5/2$, $4s1/2$ and $3d3/2$ are absolutely different. When the last neutron in the $3d5/2$, $4s1/2$ or $3d3/2$ level is only weakly bound and the rms radii of the last neutron are 8.726 fm, 10.430 fm, 9.925 fm respectively, which are greatly larger than their proton radii of 5.447 fm, 5.445 fm, 5.446 fm, respectively. This indicates that produces a neutron halo when the last neutron occupies the excited $3d5/2$, $4s1/2$ or $3d3/2$ level. This also agrees with the experimental fact[2].

In order to show clearly the normal structure for the $1i11/2$ ground state and the neutron halo for the $3d5/2$, $4s1/2$ and $3d3/2$ excited states in ^{209}Pb, we plot the density distributions of neutrons, protons, and matter, as well as the distributions of the last $3d5/2$, $4s1/2$ and $3d3/2$ neutrons in Fig. 1 for the interactions PK1. where the solid, dotted, short-dashed, and dot-dashed curves represent respectively the density distributions of neutrons, protons, and matter in ^{209}Pb, together with the distribution of the last neutron of ^{209}Pb in the levels $3d5/2$, $4s1/2$ or $3d3/2$.

Table 1. The properties of ground and excited states in ^{209}Pb from the RMF calculations with the interactions PK1, where GS and ES represent respectively the ground state and excited states with nlj denoting the quantum number of the level occupied by the last nucleon. Eexpt and Ecal represent the experimental and calculated binding energies. The rms radii of neutron, proton, and matter density distributions are denoted by R_n, R_p and R_m, respectively. $R(nlj)$ and $\varepsilon(nlj)$ represent respectively the rms radii and energies of single particle orbits.

	PK1			
	GS($1i11/2$)	ES($3d5/2$)	ES($4s1/2$)	ES($3d3/2$)
E_exp/MeV	−1640.367			
E_cal/MeV	−1639.442	−1636.934	−1636.859	−1636.402
R_n/fm	5.736	5.756	5.777	5.771
R_p/fm	5.454	5.447	5.445	5.446
R_m/fm	5.627	5.637	5.649	5.646
$R(1i11/2)$/fm	6.482			
$R(3d5/2)$/fm		8.726		
$R(4s1/2)$/fm			10.430	
$R(3d3/2)$/fm				9.925
$\varepsilon(1i11/2)$/MeV	−3.102	−3.056	−3.041	−3.048
$\varepsilon(3d5/2)$/MeV	−0.563	−0.577	−0.562	−0.559
$\varepsilon(4s1/2)$/MeV	−0.484	−0.498	−0.493	−0.482
$\varepsilon(3d3/2)$/MeV	−0.031	−0.035	−0.022	−0.038

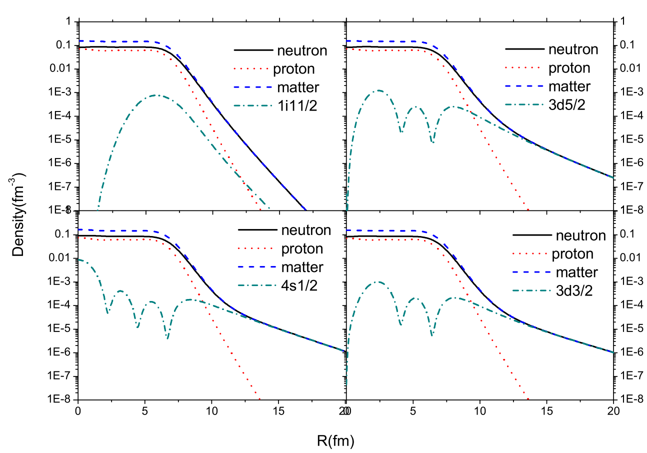

Fig. 1. The density distribution of neutron, proton, matter, and the last neutron for the ground State and excited states in ^{209}Pb with the interactions PK1, where nlj in parentheses denotes the quantum number of the level occupied by the last nucleon.

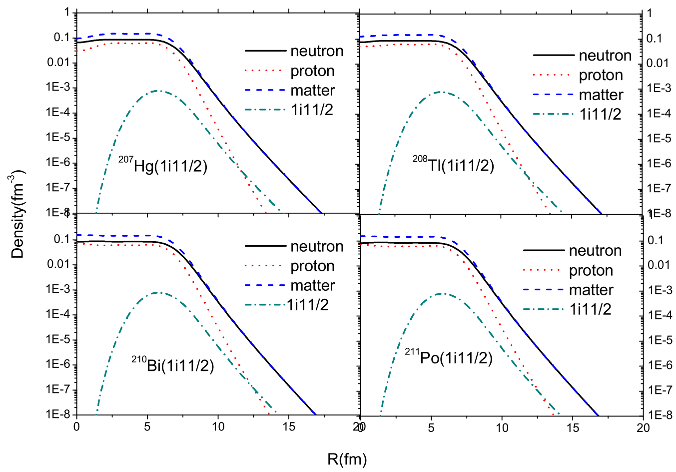

Fig. 2. The density distribution of neutron, proton, matter, and the last neutron for the ground state in ^{207}Hg, ^{208}Tl, ^{210}Bi and ^{211}Po from the RMF calculations with the interactions PK1, where nlj in parentheses denotes the quantum number of the level occupied by the last nucleon.

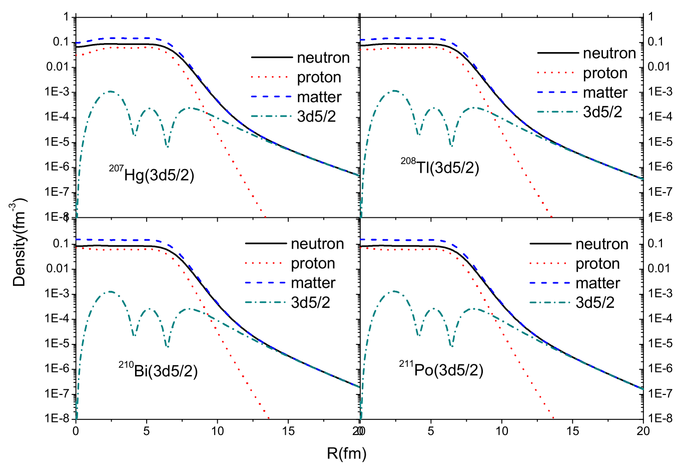

Fig. 3. Same as Fig. 2, but for the excited state of $3d5/2$ in ^{207}Hg, ^{208}Tl, ^{210}Bi, and ^{211}Po.

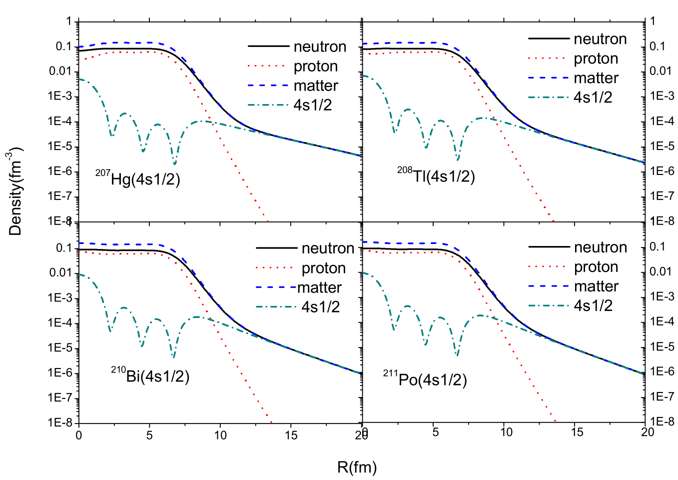

Fig. 4. Same as Fig. 2, but for the excited state of $4s1/2$ in ^{207}Hg, ^{208}Tl, ^{210}Bi, and ^{211}Po.

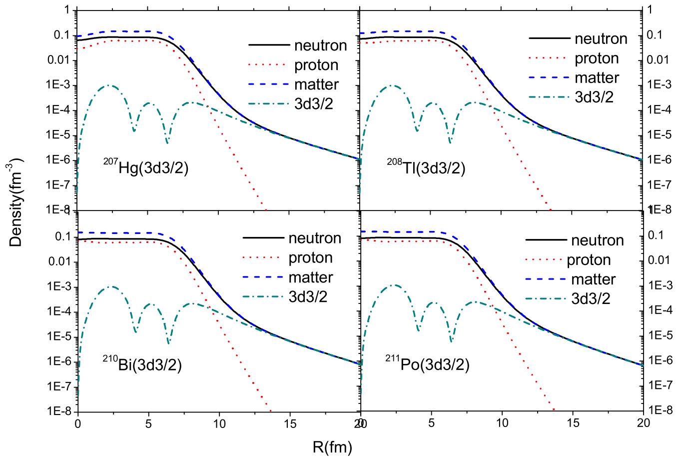

Fig. 5. Same as Fig. 2, but for the excited state of $3d3/2$ in ^{207}Hg, ^{208}Tl, ^{210}Bi and ^{211}Po.

Besides ^{209}Pb, we have performed the same calculations for ^{207}Hg, ^{208}Tl, ^{210}Bi and ^{211}Po with the effective interactions PK1. In order to make it clear, we display the density distributions of neutrons, protons, and matter in Fig. 2 for the ground state with the last neutron populating on the level $1i11/2$ and we also display the density distributions of neutrons, protons, and matter in Figs. 3—5 for the excited states with the last neutron populating on the level $3d5/2$, $4s1/2$ or $3d3/2$. from the RMF calculations with PK1.

4 Conclusion

In conclusion, the isotones with $N = 127$ are investigated systemically by using the nonlinear relativistic mean-field theory. The properties of the ground and excited states are described very well for ^{207}Hg, ^{208}Tl, ^{210}Bi, ^{211}Po and ^{209}Pb. In particular, it is predicted that there exists a neutron halo in the excited states in ^{209}Pb from the calculations with PK1. The same results are also obtained for ^{207}Hg, ^{208}Tl, ^{210}Bi and ^{211}Po. Besides the calculated binding energies which are in excellent agreement with the data available, it is also predicted that there exists a neutron halo in the excited states of ^{207}Hg, ^{208}Tl, ^{210}Bi and ^{211}Po, which is consistent with the results for ^{209}Pb.

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