Structures of $N=7$ and $N=8$ isotones with l^2 coupling*

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Abstract The structures of $N=7$ and $N=8$ isotones in Be-F mass range are investigated in the framework of the single-particle shell model. Different from the traditional potential terms, the l^2 coupling is included in the average nuclear potential. Calculations give a unified description for the structures of all studied nuclei. The neutron *s-p* level inversion in ^{11}Be and proton *s-d* level inversion in ^{16}F are simultaneously reproduced. In addition, the neutron halo structures in ^{11}Be($2s_{1/2}$) and ^{11}Be($1p_{1/2}$) are obtained. The proton halo in the first-excited state of ^{17}F is also discussed.

Key words shell model, l^2 coupling, level inversion

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1 Introduction

Due to the development of the accelerator and radioactive beam techniques, a lot of experimental investigations have been performed for exotic nuclei. Some abnormal phenomena were found. One of the most interesting findings is the change of level sequence in some light exotic nuclei. For example, the ground-state parity inversion has been found in ^{11}Be[1]. The *s-d* level inversion was indicated in the unbound nucleus ^{16}F[2]. The shifted ground state of ^{11}Be was detected to be halo state[3]. Motivated by these unexpected experimental facts, a lot of theoretical studies have been carried out[4—9]. These calculations are based on various theoretical models and are successful in different aspects. However, the physical origins for these anomalous characters are still pending and more theoretical works are needed.

As we know, few attempts have been made to explain the abnormal properties of exotic nuclei by introducing the l^2 coupling into the average nuclear potential. In the present paper, we try an effort to fill this gap. The structures of $N=7$ and $N=8$ isotones with Z=4—9 are investigated in the single-particle shell model. Since a unified description could not be obtained by only considering the conventional potential terms, the l^2 term is introduced in the average nuclear potential. The aim of our work is to explore the possibility of the l^2 coupling instead of providing complicated calculations. It is very interesting to see whether the level inversion in ^{11}Be and ^{16}F can be simultaneously reproduced by adding this new term.

2 Theoretical framework

In the single-particle shell model, the central potential usually includes the Woods-Saxon potential, spin-orbit potential and Coulomb potential[10]. In the present work, the parameters we use are $r_0=1.27$ fm, $a_0=0.67$ fm, $V_{\rm ls}=0.44V_0$ and [10]

$$V_0(\mathrm{MeV})=\begin{cases}55+30\times(N-Z)/A, & \text{for protons,}\\ 55-30\times(N-Z)/A, & \text{for neutrons.}\end{cases} \quad (1)$$

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Besides these conventional terms, we introduce the l^2 coupling $U_{ll}(r)$ into the central potential. In analogy to the spin-orbit potential, we take

$$U_{ll}(r) = V_{ll}\, r_0^2\, \frac{1}{r}\, \frac{\mathrm{d}f(r)}{\mathrm{d}r}\, (l^2-1). \qquad (2)$$

The parameter V_{ll} is different for protons and neutrons. It is defined as

$$V_{ll(\mathrm{p})} = -9.6\times\left(\frac{|N-Z|}{A}\right)\left(\frac{Z-Z_{\mathrm{m}}}{A}\right)V_{\mathrm{ls}}, \qquad (3)$$

and

$$V_{ll(\mathrm{n})} = -9.6\times\left(\frac{|N-Z|}{A}\right)\left(\frac{N-N_{\mathrm{m}}}{A}\right)V_{\mathrm{ls}}. \qquad (4)$$

Here, Z_{m} and N_{m} are the proton and neutron numbers of the full-filled major shell, respectively.

Because the l^2 term is the new term introduced by us, let us give it a microscopic explanation. Firstly, this term is allowed from the viewpoint of quantum field theory. This is because it is a scalar and does not violate the basic laws. Secondly, from the phenomenological forms of nucleon-nucleon interactions, it is well accepted that there are four central potential terms and two non-central terms. Due to the complexity of the nuclear many-body calculations, the Wigner term and the spin-orbit term are often used for the calculations of finite nuclei near stability . We consider that the l^2 term could be from the average effect of the Majorana term and other terms from phenomenological viewpoint. Thirdly, the quark model is the basic model for nuclei and nucleons from microscopic aspect of the strong interaction. It is written in the textbook of nuclear physics[11] that there appears orbit-orbit term when the relativistic effect of quark model is included. So the l^2 term can be approximately derived from Quantum Chromodynamics and it is interesting in microscopic theory.

3 Theoretical results and analysis

As we introduce a new term into the traditional model, it is necessary to test the validity of the model for the magic nuclei. So we firstly investigate the properties of $N=8$ isotones. The theoretical single-particle energies are listed in Table 1. As seen from Table 1 that the obtained level sequences of $N=8$ isotones are consistent with those of the conventional shell structure. The model prediction on the occupation of the valence nucleon agrees with the experimental facts[12, 13]. Among $N=8$ isotones, the proton-rich nucleus ^{17}F is of particular interest. Its first-excited state was detected to be proton halo state with the valence proton occupying the $2s_{1/2}$ orbit[14]. This finding motivates the theoretical investigation of ^{17}F. Our calculations show that the proton in $2s_{1/2}$ orbit of ^{17}F is bounded by only 0.74 MeV and has a relatively large radius 5.00 fm. This sharp increase of orbital radius gives hint on the halo structure of ^{17}F$(2s_{1/2})$. So we plot the density distributions of ^{17}F in Fig. 1. It is clear that the matter density distribution has a long tail when the valence proton occupies the $2s_{1/2}$ state. This manifests the one-proton halo structure in ^{17}F$(2s_{1/2})$ and agrees with the previous theoretical study[15]. The halo state in ^{17}F indicates that the proton halo of sd-shell develops for the $2s_{1/2}$ state rather than the $1d_{5/2}$ state. This behavior of proton halo is similar to that of neutron halo.

Table 1. The theoretical single-particle energies of $N=8$ isotones (in unit of MeV).

	$1s_{1/2}$ (p)	$1p_{3/2}$ (p)	$1p_{1/2}$ (p)	$1d_{5/2}$ (p)	$1s_{1/2}$ (n)	$1p_{3/2}$ (n)	$1p_{1/2}$ (n)
^{17}F	−27.72	−14.83	−9.50	−2.07	−35.15	−21.62	−15.88
^{16}O	−28.84	−15.71	−10.00		−32.99	−19.41	−13.67
^{15}N	−30.99	−15.66	−9.55		−30.61	−17.04	−11.36
^{14}C	−33.30	−15.71			−27.99	−14.49	−8.94
^{13}B	−35.67	−15.99			−25.09	−11.75	−6.45
^{12}Be	−37.91	−16.77			−21.88	−8.83	−3.96

The calculated results of $N=7$ isotones are given in Table 2. The excited-state energy is given in the bracket. From the values listed in the last two columns of Table 2, we see that the two neutron levels $1p_{1/2}$ and $2s_{1/2}$ become more closer with the increase of neutron excess. For ^{15}O and ^{13}C, the calculated values of s-p level spacing are 8.45 MeV and 6.02 MeV, respectively. They are larger than the observed values 5.18 MeV and 3.09 MeV[16], but are very close to the results 8.2 MeV and 6.3 MeV obtained from the deformed Skyrme-Hartree-Fock model[6]. For ^{11}Be, the theoretical spacing is −0.30 MeV which agrees well with the experimental data −0.32 MeV[16]. Based on these theoretical values, we conclude that the neutron *s*-*p* level spacing gradually diminishes with the increase of neutron excess. And the $1p_{1/2}$ and $2s_{1/2}$ levels become inverse in ^{11}Be. This inversion agrees with the abnormal spin-parity $(1/2)^+$ of ^{11}Be[12]. Another interesting nucleus is ^{16}F. According to the traditional shell prediction, the valence proton of ^{16}F should be in $1d_{5/2}$ state. However, our calculations show that the level energy of proton $1d_{5/2}$ orbit is 0.53 MeV which is about 0.2 MeV higher than that of proton $2s_{1/2}$ orbit in ^{16}F. Although the proton *s*-*d* inversion in ^{16}F is in contradiction with the traditional shell structure, it agrees with the observed level sequence[2].

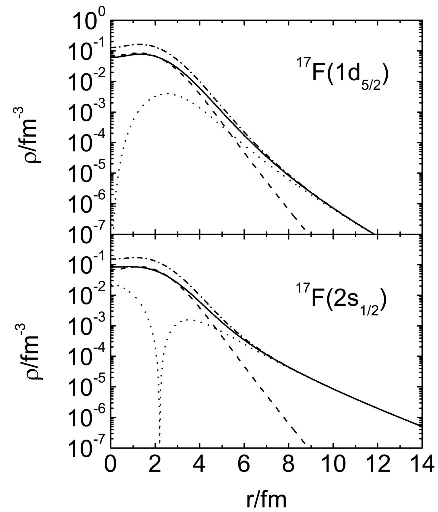

Fig. 1. The density distributions for the $\frac{5}{2}^+$ and $\frac{1}{2}^+$ states in ^{17}F. The dash-dotted, dashed, solid and dotted curves are the density distributions of matter, neutrons, protons and the last proton, respectively.

Table 2. The theoretical single-particle energies of $N=7$ isotones (in unit of MeV).

	$1s_{1/2}$ (p)	$1p_{3/2}$ (p)	$1p_{1/2}$ (p)	$2s_{1/2}$ (p)	$1s_{1/2}$ (n)	$1p_{3/2}$ (n)	$1p_{1/2}$ (n)	$2s_{1/2}$ (n)
^{16}F	−25.50	−12.38	−7.13	+0.35	−37.42	−20.52	−14.38	(−6.32)
^{15}O	−26.40	−13.32	−7.69		−34.62	−18.90	−12.75	(−4.30)
^{14}N	−27.67	−14.05	−8.00		−31.36	−17.31	−11.20	(−2.36)
^{13}C	−30.04	−13.85			−29.75	−13.49	−7.58	(−1.56)
^{12}B	−32.54	−13.83			−28.25	−9.19	−3.71	(−0.91)
^{11}Be	−34.96	−14.25			−26.91	−4.51	(−0.13)	−0.43

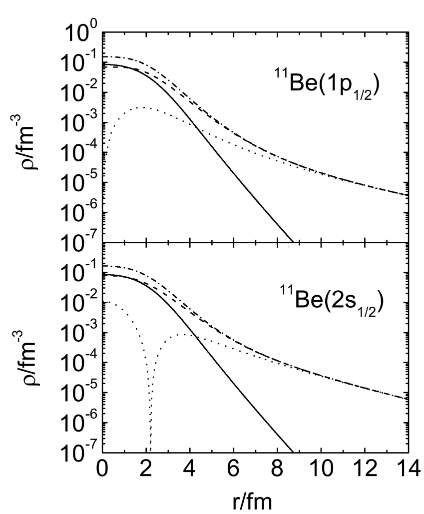

Fig. 2. The density distributions for the $\frac{1}{2}^+$ and $\frac{1}{2}^-$ states in ^{11}Be. The dash-dotted, dashed, solid and dotted curves are the density distributions of matter, neutrons, protons and the last neutron, respectively.

It is well known that the ground state and first-excited state of ^{11}Be are all halo states[3]. Based on our calculation, we plot the density distributions of the $(1/2^+)$ and $(1/2^-)$ states for ^{11}Be in Fig. 2. It is obvious that long tails of matter density distributions emerge both in ^{11}Be$(2s_{1/2})$ and ^{11}Be$(1p_{1/2})$. The extremely spatial extension of matter distribution is mainly due to the contribution of the last neutron. This confirms the one-neutron halo structures in the two states of ^{11}Be.

4 Conclusion

In the framework of the single-particle shell model, the structures of $N=7$ and $N=8$ isotones are systematically investigated. Besides the conventional terms, the l^2 coupling is added in the average potential. The model gives a unified description for the structures of all studied nuclei. Our calculations show: (i) the neutron s-p level spacing of $N=7$ isotones gradually diminishes with the increase of neutron excess; (ii) there exist the neutron s-p level inversion in ^{11}Be and the proton s-d level inversion in ^{16}F; (iii) there are proton halo structure in ^{17}F($2s_{1/2}$) and neutron halo structures in ^{11}Be($2s_{1/2}$), ^{11}Be($1p_{1/2}$). The agreement between theory and experiment implies that the adding of the l^2 coupling is reasonable and this is a feasible way to explain the abnormal properties of exotic nuclei.

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