Shell-model studies of the $N=14$ and 16 shell closures in neutron-rich nuclei*

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Abstract Shell-model studies on the $N=14$ and 16 shell closures in neutron-rich Be, C, O and Ne isotopes are presented. We calculate, with the WBT interaction, the excited states in these nuclei. The calculations agree with recent experiment data. Excited energies and B(E2) values are displayed to discuss the shell closures. Our results support the $N=16$ shell closure in these isotopes, while indicating a disappearance of $N=14$ shell closure in Be and C isotopes.

Key words shell closures, neutron rich nuclei, shell-model

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1 Introduction

Single-particle shell effect plays an important role in dominating the structure of atomic nuclei. The existence of magic numbers characterizes such structure. When nuclei are approaching the drip line, shell structure and the magic numbers can be very different from those in the β-stability line[1, 2]. It is fundamental and leading work to study the shell structure at the drip line. The magic numbers can be indicated by a relatively high first excited energy and a quite small $B(\text{E2},2^+_1 \rightarrow 0^+_{\text{g.s.}})$ value in some even-even nuclei. Recently, some new magic numbers at the drip line are predicted through the systematic trends of the 2^+ state.

Recent experiments extend our knowledge in the new magic numbers $N=14$ and 16[3—11]. The presence of the $N=14$ shell closure in O isotopes is based on the fact that the $B(E2)$ value in ^{22}O is small and the first 2^+ energy is 3.2 MeV comparing with a much smaller value of 1.7 MeV in ^{20}O[3, 7]. Though the first excited state of ^{24}O has not been directly measured, it is believed to be beyond the neutron-decay threshold at 3.7 MeV[4]. This is an evidence for the $N=16$ shell closure. Like these even-even nuclei, the observations of ^{23,25}O support the $N=14$ and 16 shell closures and are used for establishing the gap of these shell closures[8—10]. In Ne isotopes, the first excited 2^+ states also show the appearance of the new magic number $N=16$[3, 4]. However, the almost same 2^+ energies of ^{16,18,20}C hint the missing of the $N=14$ shell closure in C isotopes[5]. Moreover the observations of low lying states in N isotopes support a decrease $N=14$ shell closure[11].

New shell closures at drip line also attract interest in theoretical works. Changing the neutron and/or proton numbers, the interaction between them changes the single-particle energy as well as the shell closure[2]. For instance, the interaction between the $0d_{5/2}$ protons and the $0d_{3/2}$ neutrons decreases the energy of the $0d_{3/2}$ neutron orbit when the proton number in $0d_{5/2}$ orbit decreases. As a consequence, from ^{30}Si to ^{24}O, the $N=20$ shell closure disappears and the new $N=16$ shell closure appears when the proton number in $0d_{5/2}$ orbit decreases. Calculations in Antisymmetrized Molecular Dynamics[12],Hartree-Fock-Bogoliubov[13] and shell-model[14] support the $N=16$ shell closure as well. In the case of $N=14$, oblate deformation is obtained in C isotopes[15—17].

In this paper we investigate the Be, C, O and Ne

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isotopes in the frame work of nuclear shell model. Through the calculated excited energy in these nuclei, we discuss $N=14$ and 16 shell closures.

2 Shell-model calculations

The neutron rich Be, C, O and Ne nuclei can be described in the psd shell in which the ^{4}He is the inert core. The contribution of the fp and higher shells can be considered through the introduction of the effective interaction and effective operators[18—21]. Shell-model calculations are carried out with a newly-established parallel shell-model code as described in Ref. [22]. We perform the calculations in $0-1\hbar\omega$ psd model space with the WBT[23] interaction. Low-lying excited states are obtained in $N=10-18$ Be, C, O and Ne nuclei.

In these even-even nuclei, the spin parity of the first excited states is 2^+, which is consistent with almost all measured even-even nuclei[24]. The analyse on the shell structure can follow the way analyzing the first 2^+ excited energy and the E2 transition probability.

Figure 1 shows the systematic energy of the first excited 2^+ states in $N=10$–18 Be, C, O and Ne even-even nuclei. Both experimental and calculated results are presented. With a good agreement between them, the deviation is less than 500 keV except ^{28}Ne, which is consistent with the discussions in Refs. [1, 23]. All the calculated results are larger than experimental data, showing the same trends between them. In the case of ^{28}Ne, considering $N=18$ being close to the neutron $f_{7/2}$ shell, the result may be affected by the absence of the neutron $f_{7/2}$ orbit in our model space.

The results in Fig. 1 support the existence of $N=16$ shell closure due to the relatively high 2^+ energy, especially in Be, C and O isotopes. Without the contribution of the $0d_{5/2}$ protons, shell effect at $N=16$ occurs obviously. The $N=14$ shell closure appears clearly in O and Ne isotopes and disappears in Be and C isotopes. The shell-model calculations suggest a large neutron $1s_{1/2}$ and $0d_{5/2}$ configuration mixing in $N=10-14$ Be, C isotopes. The missing $N=14$ shell closure is due to this large configuration mixing. Essentially, the interaction between $0p_{3/2}$ proton and the $0d_{5/2}$ neutron may dominant this fact.

^{23}O is a special nucleus, because $N=15$ locates between the $N=14$ and 16 new magic numbers[9]. The excited spectrum of ^{23}O is important for both experiment and theory. In Fig 2, the excited spectra of ^{23}O and ^{21}C are presented. A good agreement between experiment and calculation is shown in the spectra. The ground state $1/2^+$ in ^{23}O indicates a $1s_{1/2}$ neutron plus ^{22}O core state. The excited states $5/2^+$ is $(1s_{1/2})^2$ neutron plus ^{22}O with a $0d_{5/2}$ neutron hole state and $3/2^+$ is $0d_{3/2}$ neutron plus ^{22}O state[9]. The spin parity of these states are pure single-particle states with low mixing, which is suggested by our shell-model calculations. The high excited energies of $5/2^+$ and $3/2^+$ indicate the existence of $N=14$ and 16 shell closures. The negative parity state in experiment is a state from the shell out of our model space[8]. The low energy of the $5/2^+$ in ^{21}C shows the disappearance of $N=14$ shell closure. A large configuration mixing vanishes the single-particle contribution in ^{21}C, though the spin parity is same as ^{23}O.

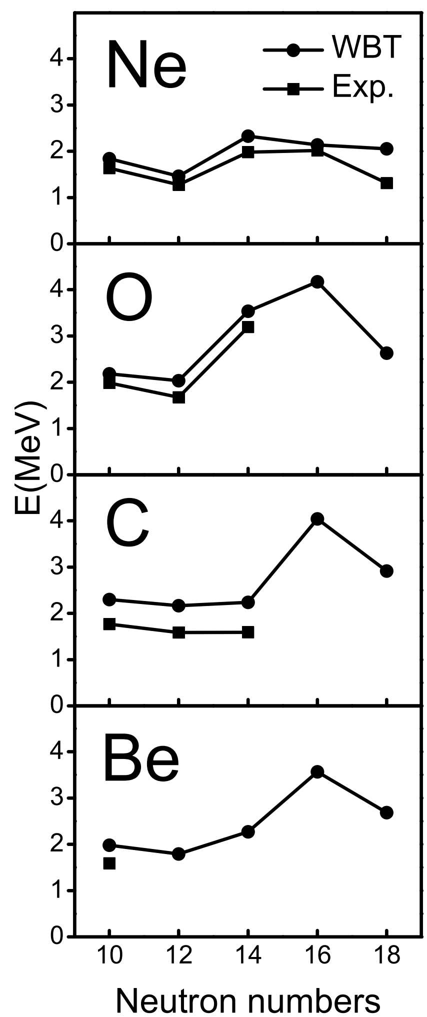

Fig. 1. Experiments and calculations of the first 2^+ state in $N=10-18$ Be, C, O and Ne even-even nuclei. Experiment data are from Ref. [24] except ^{18,20}C of which data are from Ref. [5].

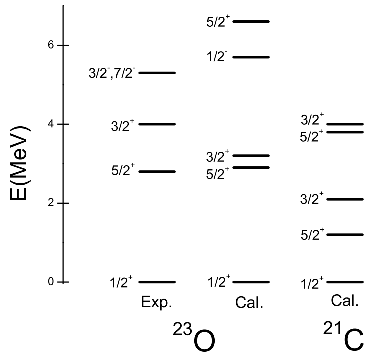

Fig. 2. Experiments and calculations of excited spectra of ^{23}O and ^{21}C. Experimental data are from Refs. [8, 9]

In Table 1, we present the $B(\mathrm{E2}, 2_1^+ \to 0_{\mathrm{g.s.}}^+)$ values of experiments and calculations in $N=10-18$ Be, C, O and Ne even-even nuclei. These B(E2) values are obtained with the single-particle harmonic-oscillator radial wave functions while the effective charges are $e_{\mathrm{p}} = 1.29$ and $e_{\mathrm{n}} = 0.49$ which are suggested in sd shell[1]. The calculated B(E2) values in O and Ne isotopes show a good agreement with experiment data. The small values at $N=14$ and 16 support the shell closures in these neutron numbers. The relatively large deviations occur in ^{18}O and ^{28}Ne. The underestimate of them may be due to the truncations in the model space. In Be and C isotopes, the values of the effective charges are still under researching[1, 25]. We can qualitatively discuss Be and C isotopes when use the same effective charges as O and Ne. The large value in ^{20}C and the small one in ^{22}C support the disappearance of $N=14$ shell closure and the appearance of the $N=16$ shell closure. The enormous B(E2) value in ^{20}C suggests a large quadrupole deformation.

Table 1. Experiments and calculations of $B(\mathrm{E2}, 2_1^+ \to 0_{\mathrm{g.s.}}^+)$ values in $N=10-18$ Be, C, O and Ne even-even nuclei. The values in parenthesis are the experimental data. Experiment data are from Ref. [24] except ^{16}C of which data are from Ref. [26]. All values are in unit e^2 fm^4.

neutron numbers	Be	C	O	Ne
10	14.14	8.570(4.15)	4.554(9.02)	59.38(68.0)
12	21.73	14.03	5.950(5.62)	52.99(46.0)
14	19.87	22.70	4.974(4.20)	42.15(34.0)
16	21.13	6.273	2.364	38.14(45.6)
18	16.88	9.021	2.992	33.41(54.0)

3 Summary and outlook

In summary, shell-model calculations have been performed to study the properties of neutron-rich Be, C, O and Ne nuclei. There is a good agreement between experiment and calculation. Our results support the existence of $N=16$ shell closure in this area, especially in the Be, C and O isotopes because of the absence of interaction between $0d_{5/2}$ proton and $0d_{3/2}$ neutron. The $N=14$ shell closure appears in O isotopes clearly, but vanishes in Be and C isotopes. A large configuration mixing, which induces the $N=14$ shell closure missing, occurs in $N=10-14$ Be and C isotopes. This may be introduced by the interaction between $0p_{3/2}$ proton and the $0d_{5/2}$ neutron. More works will be done in the future.

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