Spin-orbit potential in sulfur isotopes*

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Abstract The effects of the spin-orbit interaction in exotic nuclei are investigated by studying the binding energies and deformations of Si, S and Ar isotopes. The calculations were obtained by Skyrme-Hartree-Fock model with various spin-orbit potentials. The results reveal that spin-orbit potential is important in neutron rich nuclei.

Key words Skyrme force, spin-orbit interaction, exotic nuclei, sulfur isotopes

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1 Introduction

The spin-orbit interaction plays an important role in nuclear structure research. In some nuclei, a discrepancy exists between Skyrme-Hartree-Fock model and Relativistic mean field theory calculations. The differences were due to the methods in treating with the spin-orbit interaction. In Skyrme-Hartree-Fock model the spin-orbit part of nuclear force is introduced by adding a zero-range interaction term[1, 2]. However, in Relativistic mean field theory, the ρ boson can give the spin-orbit interaction naturally[3, 4]. In order to fix on the form and strength of spin-orbit interaction, in resent twenty years, many works on changing the form and strength of spin-orbit interaction were done to obtain a good result of isospin related properties[5, 6]. By increasing a new degree of freedom, some new parameter sets of Skyrme forces come into use. The new parameter is evaluated by fitting some of isospin related properties, such as binding energy and nuclear radii of isotopes. The results of these calculations agree well with the experimental results. Many new forces were widely used in stable nuclei as well as super heavy nuclei[7].

In our work, we performed a systematic study in neutron-rich nuclei, using different forms of spin-orbit coupling term in the Skyrme forces. The calculations include the binding energies and deformations of Si, S and Ar even-even isotopes. For S isotopes, we calculated the curve of binding energy, to study the ground state shape of S isotopes. The scope of our study are from $^{26}S_{10}$ to $^{52}S_{36}$, which is close to the neutron drip line.

Neutron-rich Si, S, Ar isotope is very suitable region to study exotic nuclei. In particular, with the advance of experimental technique, nuclei in this region are discovered continuously. Many special phenomena are observed in this region. Some theoretical works show that due to the reducing of $N = 28$ shell gap in neutron-rich S isotopes, the phenomena of shape coexistence could be found in this region[8]. The Relativistic mean field theory calculations can also give many important results in exotic nuclei[9, 10].

2 Model and parameters

In this paper, we preformed self-consistent Hartree-Fock calculations using Skyrme forces SkI2,

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SkI3 and SkI4[5]. These parameters have new added parameters in spin-orbit term. The Skyrme force have the normal form as[11],

$$
\begin{aligned}
V(\boldsymbol{r}_1,\boldsymbol{r}_2) = {} & t_0(1+x_0\boldsymbol{P}_\sigma)\delta(\boldsymbol{r})+ \\
& \frac{1}{2}t_1(1+x_1\boldsymbol{P}_\sigma)[\boldsymbol{p}'^2\delta(\boldsymbol{r})+\delta(\boldsymbol{r})\boldsymbol{p}^2]+ \\
& t_2(1+x_2\boldsymbol{P}_\sigma)\boldsymbol{p}'\cdot\delta(\boldsymbol{r})\boldsymbol{p}+ \\
& \frac{1}{6}t_3(1+x_3\boldsymbol{P}_\sigma)[\rho(\boldsymbol{R})]^\alpha\delta(\boldsymbol{r})+ \\
& iW_0\sigma\cdot[\boldsymbol{p}'\times\delta(\boldsymbol{r})\boldsymbol{p}], \qquad (1)
\end{aligned}
$$

where,

$$\boldsymbol{r}=\boldsymbol{r}_1-\boldsymbol{r}_2,\quad \boldsymbol{R}=\frac{1}{2}(\boldsymbol{r}_1+\boldsymbol{r}_2),\quad \boldsymbol{p}=\frac{1}{2i}(\nabla_1-\nabla_2),$$

and $\boldsymbol{p}'$ is $\boldsymbol{p}$ acting on the left.

In SkI2-4 parameter sets, a new degree of freedom is introduced[5]. In this way, for nucleon τ, the potential of spin-orbit term is,

$$W=b_4\nabla\rho+b'_4\nabla\rho_\tau.$$

the new degree reflects the isotopic spin effect in spin-orbit coupling. In usual Skyrme force, $b'_4/b_4=1$, and in Relativistic mean field theory calculations the result equals zero.

3 Results and discussions

Our results indicate different spin-orbit coupling terms can give different binding energy. The discrepancies increase in exotic nuclei. The differences between experimental and theoretical binding energy are shown in Fig. 1. The increase in the discrepancies indicate that the effect of spin-orbit coupling in Skyrme force is remarkable in exotic nuclei.

As the nuclei calculated approaching to the neutron drip line, the the discrepancies between calculated and experimental results increase, which indicate that the Skyrme forces have certain limitation in neutron-rich exonic nuclei. Among these force, the result closest to the experimental is calculated by the SkI3 force. It have the same spin-orbit coupling interaction with the Relativistic mean field theory model.

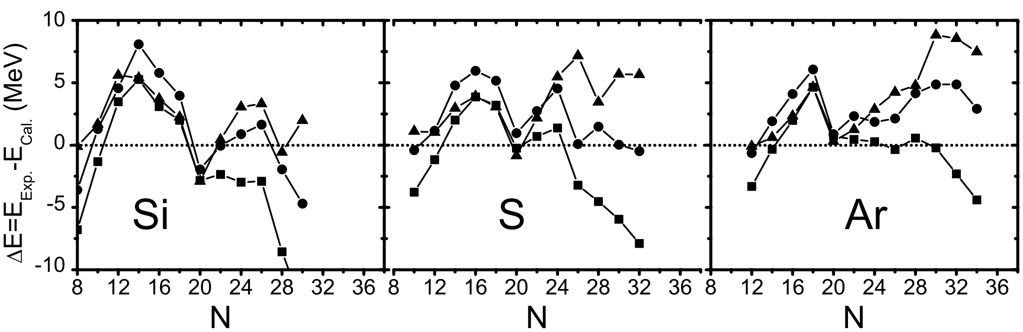

Fig. 1. Binding energy difference between experimental[12] and theoretical results of Si, S and Ar isotopes, the Skyrme forces using in the calculations are represented by triangle, dot and square, representing SkI2, SkI3 and SkI4 separately.

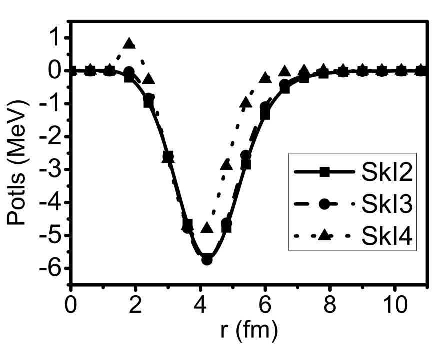

Fig. 2. The spin-orbit coupling potential in ^{44}S, the solid line, dashed line and dash-dot line representing the results of SkI2, SkI3 and SkI4 separately.

The differences in binding energy are produced by the different form of selected spin-orbit coupling interaction. The potentials of spin-orbit coupling are shown in Fig. 2. The strength of SkI4 parameter set is significantly less than the other two sets of parameters, and the strength of SkI3 force is more centralized to the surface of nuclei than that of SkI4.

The theoretical prediction of shapes in S isotopes, is a current research focus, both theoretical and experimental nuclear physicist are interested in these nuclei[8, 15]. We did calculations on the evolutions of ground state shapes of S isotopes, using these three

Skyrme forces, SkI2, SkI3 and SkI4. These forces can give similar results of deformations.

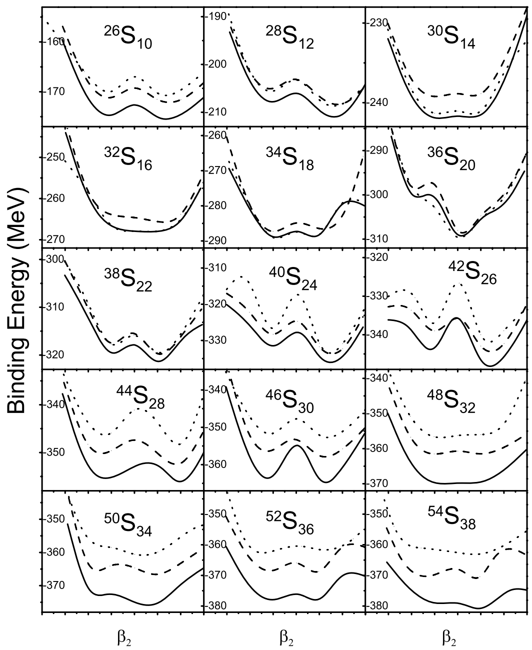

Fig. 3. The shape evolutions of S isotopes, the legends are the same as in Fig. 2.

As shown in Fig. 3, In S isotope chain, the ground state shape changes strongly, and the changes have obvious regularities. ^{26}S and ^{28}S have a long ellipsoid shape, which evolute to spherical in the magic nuclei ^{36}S. As the $1f_{7/2}$ shell are being filled, in ^{40}S and ^{42}S, the nuclei become long ellipsoid shape gradually. As the neutron number continued to increase, when the $1f_{7/2}$ shell were completely occupied, on the contrary to the situation in stable nuclei, a shape coexistence of prolate and oblate shapes emerges in the magic nuclei ^{44}S. The shape coexistence exists in the nuclei with more neutron than ^{44}S, until the neutron drip line.

More calculations show that apart from S isotopes, for the neutron-rich Si and Ar isotopes, there are other nuclei with shape coexistent properties in these region.The results agree with the previous theoretical and experimental results[13, 14]. The non-spherical ground states are due to the quenching of $1f_{7/2}$ shell closure and the mixing of f,p shell levels[15].

4 Summary

The results show that different selections of spin-orbit coupling in Skyrme force have large impacts on the results of binding energy calculations. However, nuclear deformations are less affected. The results in Ar, S and Si isotopes show that nuclear ground state shapes changes obviously in light neutron-rich exotic nuclei, some shape coexistent nuclei were found in neutron-rich Si, S and Ar isotopes. Especially, ^{44}S is shape coexistent, and ^{42}Si is oblate, which indicate the shell quenching of $N=28$ shell in neutron-rich Si, S isotopes. Further experimental results would be important in fixing the form and strength of spin-orbit coupling interaction in Skyrme force. This would be helpful in unveiling the form and strength of spin-orbit part in nuclear interactions.

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