

$^{16}\text{O} + ^{16}\text{O}$ molecular structures of superdeformed states in S isotopes

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Abstract. Structures of excited states in S isotopes are investigated by using the antisymmetrized molecular dynamics and generator coordinate method (GCM). The GCM basis wave functions are calculated via energy variation with a constraint on the quadrupole deformation parameter β . By applying the GCM after parity and angular momentum projections, the coexistence of positive- and negative-parity superdeformed (SD) bands are predicted in $^{33-36}\text{S}$ except for negative-parity states in ^{36}S . The SD bands have structures of $^{16}\text{O} + ^{16}\text{O} + \text{valence neutron(s)}$ in molecular orbitals around the two ^{16}O cores in a cluster picture. The configurations of the valence neutron(s) in the SD states are δ and/or π molecular orbitals.

1. Introduction

Clustering and deformation play important roles in nuclear structures. In S isotopes, $^{16}\text{O} + ^{16}\text{O}$ structures are expected to develop because S isotopes are analogous of Be isotopes. Be isotopes are considered to have structures of $\alpha + \alpha + \text{valence neutrons}$ in molecular orbitals[1–8]. An α and an ^{16}O are double-closed-shell nuclei, and when α is replaced with ^{16}O in Be isotopes, they become S isotopes. In fact, existence of superdeformed (SD) states that contain a large amount of $^{16}\text{O} + ^{16}\text{O}$ cluster structure components has been predicted[9, 10], which is an analogue of $\alpha + \alpha$ structure of ^8Be . The dominant components of the SD states in ^{32}S are predicted to be $4\hbar\omega$ configurations in the spherical shell-model picture.

By a γ -spectroscopy experiment, various positive- and negative-parity states have been observed[11]. Low-lying states are considered to be $0\hbar\omega$ or $2\hbar\omega$ neutron excited states. And many additional states are observed. But theoretical study about many-particle-many-hole states is insufficient.

In this paper, structures of positive- and negative-parity SD states in ^{34}S is discussed in details. The SD states have structures of $^{16}\text{O} + ^{16}\text{O}$ clusters and valence neutrons in molecular orbitals. Molecular structures developed in $^{33-36}\text{S}$ are also discussed. Details of this work is reported in Ref. [12].

2. The GCM and AMD models

In this work, wave functions of ground and excited states are calculated by using the antisymmetrized molecular dynamics (AMD) and the generator coordinate method (GCM), which is superposition of AMD wave functions to diagonalize Hamiltonian. The Gogny D1S force



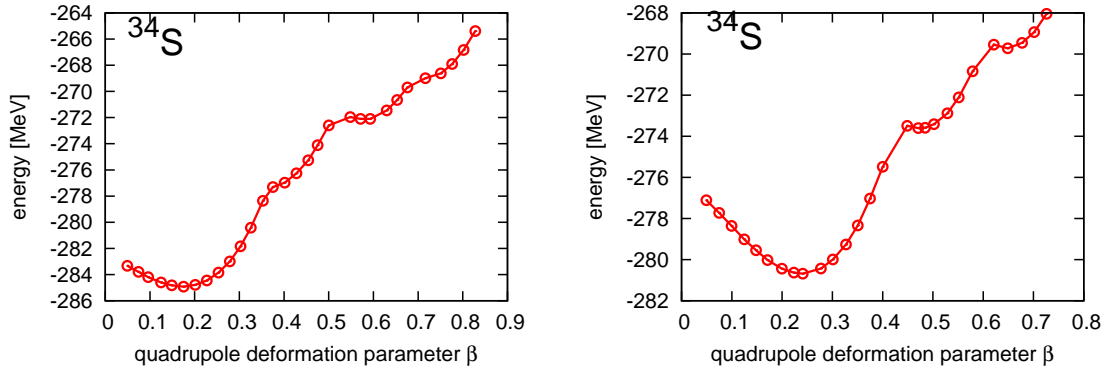


Figure 1. Energy curves of ^{34}S as functions of quadrupole deformation parameter β . Left and right panels are for positive- and negative-parity, respectively.

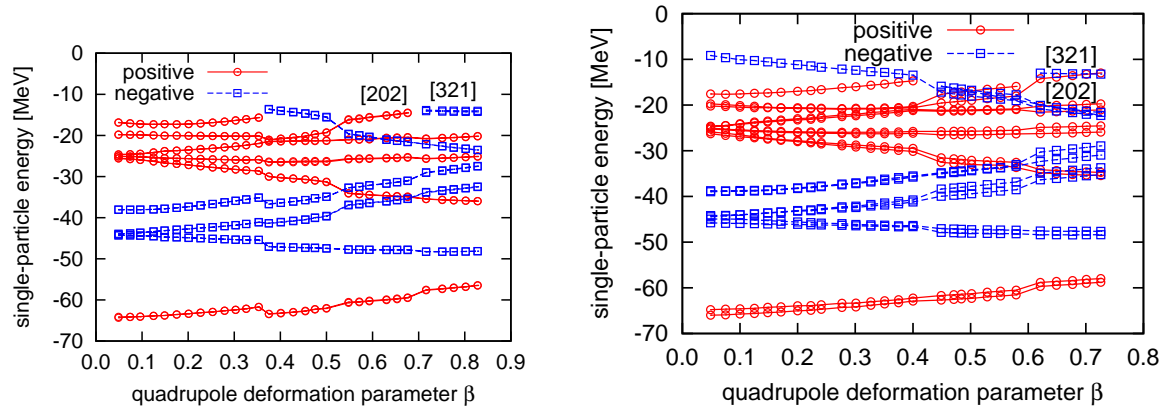


Figure 2. Single-particle energies of as functions of quadrupole deformation parameter β for positive- (left) and negative-parity (right) states. Circles and squares show positive- and negative-parity orbits, respectively. Numbers in brackets show the Nilsson quanta for the two highest orbits of neutrons in SD region. This figure is taken from Ref. [12].

is used as an effective Hamiltonian. An AMD wave function is a Slater determinant of Gaussian wave packets, and parameters in the wave functions such as position of each wave packet and spin directions are optimized by variational calculation with a constraint on quadrupole deformation parameter β . Obtained wave functions are projected onto eigen states of parity and angular momentum and superposed. Final wave functions are obtained by diagonalizing Hamiltonian.

3. Results

Figure 1 shows β -energy surface obtained by energy variational calculations for positive- and negative-parity states, respectively, in ^{34}S . β -energy surfaces have local minima and a shoulder at SD region around $\beta \sim 0.6$, which implies coexistence of positive- and negative-parity SD states.

Figure 2 shows single-particle orbits of neutrons as functions of quadrupole deformation parameter β for positive- and negative-parity states, respectively. Circles and squares show positive- and negative-parity orbits, respectively. In SD region, the two highest orbits are flat

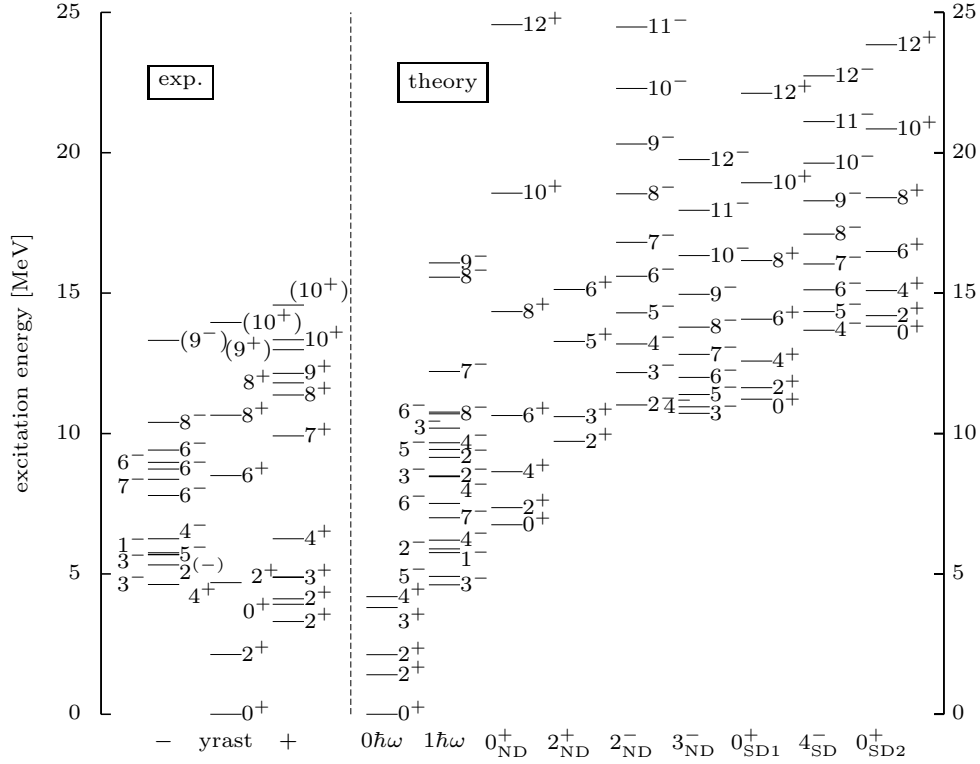


Figure 3. Left and right parts show experimental and theoretical level scheme, respectively, in ^{34}S . This figure is taken from Ref. [12].

and those Nilsson quanta are $[202]$ and $[321]$, which are positive- and negative-parity orbits, respectively. For lower 16 orbits, they have $2\hbar\omega$ excited configurations. Proton orbits have same configurations as lower 16 orbits of neutrons. Totally, the ^{32}S core part of SD region in ^{34}S has $4\hbar\omega$ excited configurations, which are same as configurations of predicted SD states in ^{32}S [$^{32}\text{S}(\text{SD})$][10]. The $^{32}\text{S}(\text{SD})$ core part has neck structure as well as a prediction of SD states. They show that structure of these wave functions are $^{32}\text{S}(\text{SD})$ core + $[202]$ and $[321]$ neutrons.

Superposing those wave functions after parity and angular momentum projection, level scheme is obtained as shown in Fig. 3. Various rotational band are obtained. Three bands labeled $K^\pi = 0_{\text{SD1}}^+$, 4_{SD}^- , and 0_{SD2}^+ , coexist, which are SD bands. Those three SD bands have multi-particle-multi-hole excited configurations for both of proton and neutron parts. Configurations of dominant components of $K^\pi = 0_{\text{SD1}}^+$, 4_{SD}^- , and 0_{SD2}^+ bands are $^{32}\text{S}(\text{SD})$ core + $[202]^2$, $[202][321]$ and $[321]^2$ valence neutrons, respectively, in the Nilsson picture.

The SD states are interpreted as $^{16}\text{O} + ^{16}\text{O}$ molecular structure in a cluster picture. Configuration of $^{32}\text{S}(\text{SD})$ core is same as those of SD states in ^{32}S , which contain a large amount of $^{16}\text{O} + ^{16}\text{O}$ cluster structure components[10]. Valence neutrons have $[202]$ and $[321]$ configurations in a Nilsson picture, and the $[202]$ and $[321]$ orbits correspond to δ and π orbitals around two ^{16}O cores, respectively, as shown in Fig. 4. The left part of Fig. 4 shows schematic pictures of phase of $0d$ orbits around two ^{16}O cores (dotted circles) for $|l_z| = 2, 1$, and 0 components. By linear combination of $0d$ around two ^{16}O cores, δ , π , and σ orbitals (right part) are generated from $|l_z| = 2, 1$, and 0 orbits, respectively, around two ^{16}O cores. Figure 4(a) shows a $|l_z| = 2$ orbital, which is a δ orbital. Superposing two $|l_z| = 2$ orbits around ^{16}O cores, a molecular orbital becomes right part. It has no node for z -direction. The $0d$ orbits has no node for radial direction, so Nilsson quanta of a δ orbital is $[202]$. Figure 4(b) shows a $|l_z| = 1$

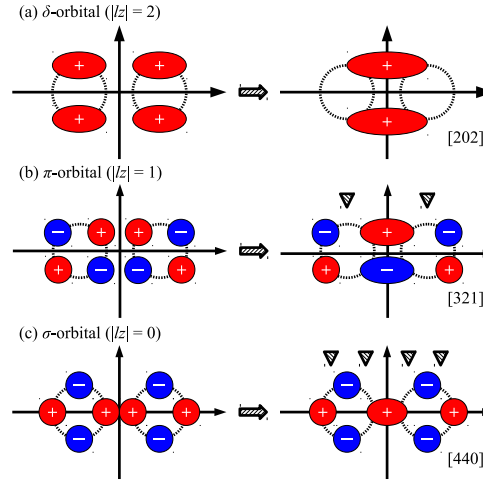


Figure 4. Schematic illustrations of molecular orbitals generated from $0d$ orbits around two ^{16}O cores for (a) δ , (b) π , and (c) σ orbitals. Horizontal axis is z -axis. Inverse triangles show locations of nodes in molecular orbitals in the z direction. Numbers in brackets show Nilsson quanta. This figure is taken from Ref. [12].

orbital, which is a π orbital. As same discussions, The π orbital have two nodes for z -directions, and Nilsson quanta of a π orbital is [321]. Figure 4(c) shows a $|l_z| = 0$ orbital, which is a σ orbital. Nilsson quanta of a σ orbital is [400]. Totally, structures of $K^\pi = 0_{\text{SD1}}^+$, 4_{SD}^- , and 0_{SD2}^+ are interpreted as $^{16}\text{O} + ^{16}\text{O} + \delta^2$, $\delta\pi$, and π^2 structures, respectively, in a cluster picture. It is predicted that $^{33-36}\text{S}$ also have positive- and negative-parity SD states with $^{16}\text{O} + ^{16}\text{O}$ molecular structure except for negative-parity states in ^{36}S .

4. Conclusions

In conclusions, structures of SD states in ^{34}S by using the AMD and the GCM. In ^{34}S , two positive-parity and one negative-parity SD bands coexist. Those structures are interpreted as $^{16}\text{O} + ^{16}\text{O} + \delta^2$, π^2 and $\delta\pi$ molecular orbitals around two ^{16}O cores. $^{33-36}\text{S}$ also have SD states except for negative-parity states in ^{36}S . They have also molecular structures. In order to understand largely deformed states in $N \neq Z$ nuclei, clustering and molecular orbital around the cluster core are important.

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