EPJ Web of Conferences **117**, 04009 (2016) DOI: 10.1051/epjconf/201611704009
NN2015

^{16}O + ^{16}O molecular structures of positive- and negative-parity superdeformed bands in ^{34}S

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Abstract

The structures of excited states in ^{34}S are investigated 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 two positive- and one negative-parity superdeformed (SD) bands are predicted, and low-lying states and other deformed bands are obtained. The SD bands have structures of ^{16}O + ^{16}O + two valence neutrons in molecular orbitals around the two ^{16}O cores in a cluster picture. The configurations of the two valence neutrons are δ^2 and π^2 for the positive-parity SD bands and $\pi^1\delta^1$ for the negative-parity SD band.

S isotopes ($Z = 16$) are suitable nuclei for studying deformation and clustering caused by excitation. S isotopes are expected to be favorable for the formation of SD bands because $Z = 16$ is considered a magic number of superdeformation. In terms of clustering, S isotopes are key nuclei in the *sd* shell. S isotopes are analogs of Be isotopes because those isotopes can form systems consisting of two doubly closed shell nuclei (^{16}O and α for S and Be isotopes, respectively) and valence neutrons. In Be isotopes, structures

consisting of $\alpha + \alpha +$ valence neutrons in molecular orbitals are thought to develop in low-lying states, with the valence neutrons in molecular orbitals around two α cores [1]. The SD states in ^{32}S are predicted to contain a large amount of ^{16}O + ^{16}O cluster structure components [2,3]. They suggest the existence of SD states that have ^{16}O + ^{16}O + valence neutrons in the molecular orbital structure in S isotopes. By a γ spectroscopy experiment, many states up to the $J^\pi = 10^+$ and (9^-) are observed in ^{34}S. But the structures with multi-particle-multi-hole configurations have never been clarified. This paper aims to clarify the structures of SD states in ^{34}S theoretically using antisymmetrized molecular dynamics (AMD) and the generator coordinate method (GCM). The coexistence of positive- and negative-parity SD bands and their structures are discussed, focusing on ^{16}O + ^{16}O + valence neutrons in molecular orbitals around the two ^{16}O cores. Details of this study was reported in Ref. [4].

The wave functions in low-lying states are obtained using parity projection and angular momentum projection (AMP) and the GCM with deformed-basis AMD wave functions. A deformed-basis AMD wave function is a Slater determinant of Gaussian wave packets. The basis wave functions of the GCM are obtained by energy variation with a constraint on quadrupole deformation parameter β after projection onto eigenstates of parity. The optimized wave functions are superposed after parity projection and AMP by employing the quadrupole deformation parameter β. Then we obtain the energy spectra and the corresponding wave functions. Gogny D1S force is used as the effective interaction.

Figures 1 and 2 show the energy surfaces as functions of the quadrupole deformation parameter β for the positive- and negative-parity states, respectively, obtained by energy variation with a constraint on β after parity projection. The energies projected onto the $J^\pi = 0^+$, 3^-, and 4^- states are also shown. In the positive-parity energy surface (Fig. 1), three excited local minima or shoulders exist around $\beta = 0.4$, 0.6, and 0.8 as well as the minimum at $\beta = 0.25$, which suggest the existence of three excited deformed bands in the positive-parity states. In the negative-parity energy surface (Fig. 2), three local minima exist around $\beta = 0.2$, 0.5, and 0.7.

Figures 3 and 4 show the single-particle energies as functions of the quadrupole deformation β for positive- and negative-parity states, respectively. The quanta $[Nn_z\Omega]$ in the Nilsson picture are also shown for the two highest orbits of neutrons in $\beta > 0.6$ region, which have [202] and [321] as shown in the figures. The single-particle energies of [202] and [321] are flat for the quadrupole deformation parameter β, and they resemble each other. Left and center panels in Fig. 5 show the density distributions of the

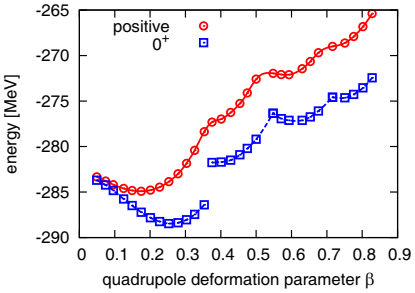

Figure 1: Energy surfaces as functions of quadrupole deformation parameter β for positive-parity states. Circles and squares show energies projected onto positive-parity and $J^\pi = 0^+$ states, respectively. This figure is taken form Ref. [4].

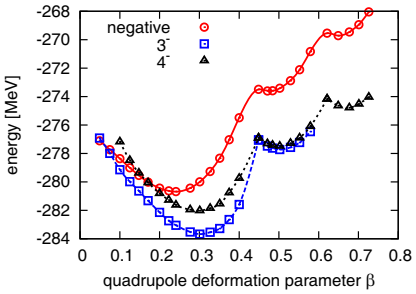

Figure 2: Energy surfaces as functions of quadrupole deformation parameter β for negative-parity states. Circles, squares, and triangles show energies projected onto positive-parity, $J^\pi = 3^-$, and $J^\pi = 4^-$ states, respectively. This figure is taken form Ref. [4].

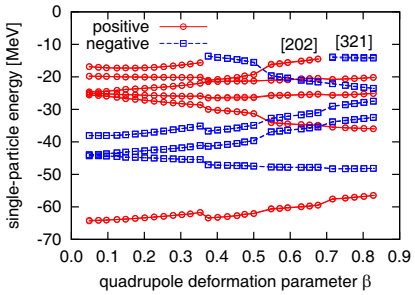

Figure 3: Single-particle energies of neutrons as functions of quadrupole deformation parameter β for positive-parity states. Circles and squares show positive- and negative-parity orbits, respectively. Numbers in brackets show the Nilsson quanta for the two highest orbits of neutrons (see text). This figure is taken form Ref. [4].

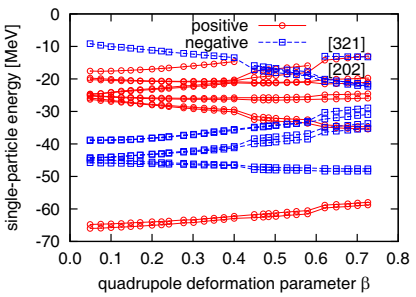

Figure 4: Same as Fig. 3 but for negative-parity states. This figure is taken form Ref. [4].

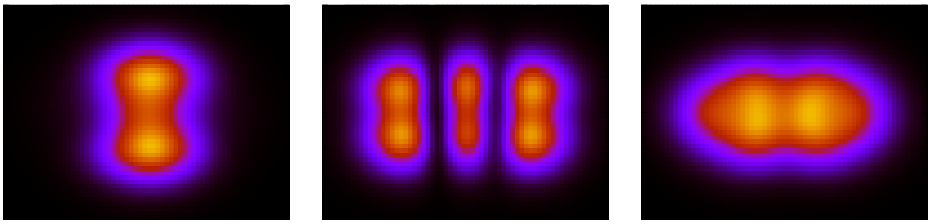

Figure 5: Density distributions of [202] (left) and [321] (center) neutron orbits and that of lower 16 protons and 16 neutrons in $\beta > 0.6$ region.

[202] and [321] orbits, respectively. The ^{32}S core part have neck structures in $\beta > 0.6$ region as shown in the right panel in Fig. 5, and the ^{32}S core part have $4\hbar\omega$ excited configuration, which is similar to SD states in ^{32}S. On the energy surface, ^{32}S (SD) core + $[202]^2_\nu$ and $[321]^2_\nu$ configurations are obtained in positive-parity states, and ^{32}S (SD) core + $[202]^1_\nu[321]^1_\nu$ configurations are obtained in negative-parity states.

Figure 6 shows the level scheme of the positive- and negative-parity states. Various rotational bands, called $K^\pi = 0^+_{\rm ND}$, $0^+_{\rm SD1}$, and $0^+_{\rm SD2}$ for positive parity and $K^\pi = 2^-_{\rm ND}$, $3^-_{\rm ND}$, and $4^-_{\rm SD}$ for negative parity, are obtained, as well as low-lying $0\hbar\omega$ and $1\hbar\omega$ states. The dominant components of the $K^\pi = 0^+_{\rm SD1}$ and $0^+_{\rm SD2}$ bands have ^{32}S (SD) core + $[202]^2_\nu$ and $[321]^2_\nu$ configurations, respectively, and those of the $K^\pi = 3^-_{\rm ND}$ and $2^-_{\rm ND}$ bands have ^{32}S (SD) core + $[202]^1_\nu[321]^1_\nu$ configurations.

The [202] and [321] Nilsson orbits correspond to δ and π molecular orbitals around the ^{16}O + ^{16}O cores. The lowest orbit around an ^{16}O core is a $0d_{5/2}$ orbit. By linear combination of $0d_{5/2}$ orbits around two ^{16}O cores, molecular orbitals around the two ^{16}O cores are formed. Figure 7 shows schematic illustrations of the formation of molecular orbitals around two spherical ^{16}O cores. The $0d_{5/2}$ orbits around the ^{16}O cores form δ and π orbitals, which are formed from two $(l, |l_z|) = (2, 2)$ and $(2, 1)$ orbits, respectively, around the left and right ^{16}O cores. For the δ orbital, the $(l, |l_z|) = (2, 2)$ orbits have no node in the z direction, as shown in the left column of Fig. 7(a). Therefore, the δ orbital also has no node in the z direction, as shown in the right column of Fig. 7(a), and the numbers of nodes of the π orbitals are two in the direction of the z axis, as shown in Fig. 7(b). In the radial direction, they have no node because a $0d$ orbit has no node in the radial direction. This shows that the quanta of the δ and π orbitals are [202] and [321], respectively, in the Nilsson picture.

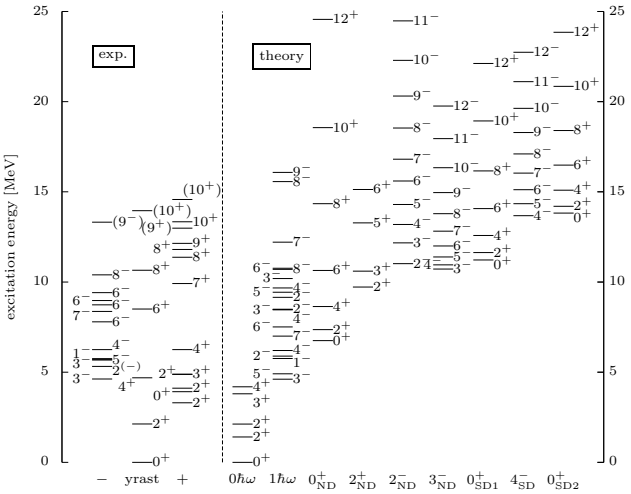

Figure 6: Left and right parts show experimental and theoretical level scheme, respectively, in ^{34}S. The "yrast" and "+" in the experimental part show yrast states and other positive-parity states, respectively, and the "−" shows negative-parity states. In the theoretical part, dominant components and labels of rotational bands are shown (see text). This figure is taken form Ref. [4].

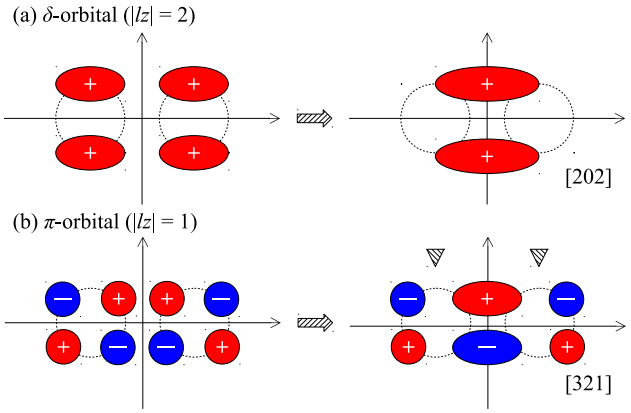

Figure 7: Schematic illustrations of molecular orbitals generated from 0d orbits around two ^{16}O cores for (a) δ and (b) π orbitals. Left and right columns show phases of 0d orbits around two ^{16}O cores and molecular orbitals, respectively. Dotted circles show two ^{16}O cores located on the z axis. Inverse triangles show locations of nodes in molecular orbitals in the z direction. Numbers in brackets show Nilsson quanta (see text). This figure is taken form Ref. [4].

The GCM calculation yielded three SD bands, called the $K^\pi = 0^+_{\rm SD1}$, $0^+_{\rm SD2}$, and $4^-_{\rm SD}$ bands, the structures of which are interpreted as ^{16}O + ^{16}O + two valence neutrons that have δ^2, π^2, and $\delta^1\pi^1$ configurations, respectively, in a cluster picture. The ^{32}S core part of the $K^\pi = 0^+_{\rm SD1}$, $0^+_{\rm SD2}$, and $4^-_{\rm SD}$ band members are same as SD states in ^{32}S, which contains a large amount of ^{16}O + ^{16}O cluster structure components [3]. Therefore, the three SD bands have structures of ^{16}O + ^{16}O + valence neutrons in a cluster picture. The configurations of the valence neutrons of the $K^\pi = 0^+_{\rm SD1}$, $0^+_{\rm SD2}$, and $4^-_{\rm SD}$ bands are $[202]^2$, $[321]^2$, and $[202]^1[321]^2$, respectively. The [202] and [321] orbits correspond to the δ and π molecular orbitals, respectively, around the two ^{16}O cores. Therefore, the configurations of the valence neutrons of the $K^\pi = 0^+_{\rm SD1}$, $0^+_{\rm SD2}$, and $4^-_{\rm SD}$ bands are interpreted as δ^2, π^2, and $\delta^1\pi^1$, respectively.

In conclusions, the structure of the SD states in ^{34}S were investigated using the AMD and GCM. By superposing the AMD wave functions calculated via energy variation with a constraint on the quadrupole deformation parameter β, the coexistence of two positive- and one negative-parity SD bands is predicted. The SD states have mp-mh configurations, and they are interpreted as a structure consisting of ^{16}O + ^{16}O + valence neutrons in molecular orbitals around ^{16}O + ^{16}O cores in a cluster picture. Both of clustering and deformation are important to understand structures in $A \gtrsim 30$ nuclei.

This work was supported by JSPS KAKENHI Grant Number 25800124. The numerical calculations for this work were conducted under the Interdisciplinary Computational Science Program of the Center for Computational Sciences, University of Tsukuba.

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