Quadrupole and octupole softness in the $N = Z$ nucleus $^{64}$Ge

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Quadrupole and octupole softness in the even-even $N = Z$ nucleus $^{64}$Ge is studied on the spherical shell model basis. We carry out the shell model calculation using the pairing plus quadrupole ($QQ$) plus octupole ($OO$) interaction with monopole corrections. It is shown that $^{64}$Ge is an unstable nucleus with respect to both the quadrupole and octupole deformations, which is consistent with the previous discussions predicting the $\gamma$ softness and octupole instability. It is demonstrated that proton-neutron part $Q_pQ_n$ of the $QQ$ interaction is important for the $\gamma$ softness or triaxiality.

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Heavy $N = Z$ nuclei with $A = 56 \sim 80$ show strong shape variations such as prolate shape, oblate shape, prolate-oblate shape coexistence, and $\gamma$ softness, depending on the mass number. These nuclei lie in transitional regions from spherical shape (e.g., $^{56}$Ni$^{\text{I}}$) to strong prolate deformation (e.g., $^{80}$Zr$^{\text{I}}$). The $N = Z = 32$ nucleus $^{64}$Ge$^{32}$ is known to be a typical example showing $\gamma$-soft structure in $N = Z$ proton-rich unstable nucleus, according to theoretical calculations based on the mean-field approximation. The calculations predict probable $\gamma$ instability in the ground state, and triaxiality in the excited states, i.e., the quadrupole deformation $\beta_2 \sim 0.22$ and $\gamma \sim 27^\circ$.

Deformed shell model calculations predict that the nucleon numbers 34, 56, 88, and 134 are strongly octupole driving in nuclei where the Fermi surface lies near single-particle levels with $\Delta l = \Delta j = 3$. We can expect that nuclei with $N = Z$ near the octupole magic numbers exhibit an especially strong octupole effect, because neutrons and protons contribute cooperatively. This does not necessarily mean a permanent octupole deformation. The level pattern of negative-parity states in $^{64}$Ge is not a rotational one, and the sequence of the $3^-\sim 7^-$ levels is irregularly spaced. Thus, $^{64}$Ge is an $N = Z$ proton-rich unstable nucleus manifesting a soft structure with respect to quadrupole and octupole deformations, from experimental and theoretical evidences. In fact, inclusion of the $\gamma$ deformation improves the $E2$ transitions of negative-parity states in $^{68}$Ge.

The spherical shell model approach could be more appropriate for describing various aspects of nuclear structure. It is desirable to add the $g_{9/2}$ orbital to the full $pf$ shell ($f_{7/2}, p_{3/2}, f_{5/2}, p_{1/2}$) for studying both positive and negative parity states of $^{64}$Ge, but the shell model calculation in this space is impractical at present because of the huge dimension. So we restrict the model space to the $p_{3/2}, f_{5/2}, p_{1/2}$, and $g_{9/2}$ orbitals, and carry out the shell model calculation with the recently developed shell model code. There are few effective shell-model interactions in this model space.

Recently, an extended $P + QQ$ force was applied to the $f_{7/2}$-shell nuclei. This interaction is schematic but works remarkably well. The conventional $P + QQ$ force was first suggested by Bohr and Mottelson, and widely used by Kisslinger and Sorensen, Baranger and Kumar, and many authors. Unlike the original application to heavy nuclei, the extended $P + QQ$ interaction is isospin-invariant. In this Rapid Communication, we introduce the octupole-octupole ($OO$) force into the extended $P + QQ$ force model to describe negative-parity states. This interaction is quite useful for studying not only the $\gamma$ softness but also the octupole instability mentioned above. The $QQ$ and $OO$ forces are the long-range and the deformation-driving part of the effective interaction. Contrary to this, the monopole pairing force can be associated with short-range force, and restores the spherical shape. Thus, the competitions among the $QQ$, $OO$, and monopole pairing forces are expected to be important for shape transitions of quadrupole and octupole deformations in $^{64}$Ge. The $P + QQ$ force with the $OO$ interaction will be suitable for studying the monopole pairing, quadrupole, and octupole correlations. Recently, the $fp$ shell model calculation with the FPD6 interaction has been performed in $^{64}$Ge as a test case for quantum Monte Carlo diagonalization (QMC) method. The projected shell model calculation has been performed in $^{64}$Ge modifying the standard Nilsson parameters.

Since protons and neutrons in the $N = Z$ nuclei occupy the same levels, one would expect strong proton-neutron ($p-n$) interactions. In particular, one of the most interesting questions in the study of nuclear structure is what role the $p-n$ interaction play in the nuclear deformation. The long-range $p-n$ isoscalar ($T = 0$) interaction between valence nucleons has been suggested to be a source of the nuclear deformation. On the other hand, the isoscalar $QQ$ interaction used in the $P + QQ$ force model has very strong $p-n$ component $Q_pQ_n$, which gives rise to nuclear quadrupole deformation. The $Q_pQ_n$ interaction is expected to be important for quadrupole collectivity in $^{64}$Ge. The rotational
behavior of $T = 0$ and $T = 1$ bands in the odd-odd $N = Z$ nucleus $^{62}$Ga is recently studied using the spherical shell model and the cranked Nilsson-Strutinsky model \cite{8}.

In order to study the octupole correlation, let us introduce an isoscalar octupole interaction $H_{OO}$ with the force strength $\chi_3$ to the extended $P + QQ$ model \cite{8} with monopole corrections $H_{m}^{\text{corr}}$:

$$H = H_0 + H_{P0} + H_{P2} + H_{QQ} + H_{OO} + H_{m}^{\text{corr}} = \sum_\alpha \varepsilon_\alpha c_\alpha^\dagger c_\alpha - \sum J = 0,2 \sum_{M\kappa} P_{JM}^{\alpha} P_{JM\kappa} + \frac{1}{2} \sum_{M} \chi_2 : Q_{2M}^\dagger Q_{2M} : - \frac{1}{2} \sum_{M} \chi_3 : O_3^{\alpha} O_{3M} : + H_{m}^{\text{corr}}, $$

(1)

where $\varepsilon_\alpha$ is a single-particle energy, $P_{JMT\kappa}$ is the pair operator with angular momentum $J$ and isospin $T$, and $Q_{2M}$ $(O_{3M})$ is the isoscalar quadrupole (octupole) operator. Due to the isospin-invariance, each term of the above Hamiltonian includes $p-n$ components, which play important roles in $N = Z$ nuclei.

We carried out shell model calculations in a model space restricted to the $2p_{3/2}, 1f_{5/2}, 2p_{1/2},$ and $1g_{9/2}$ orbitals (called $pfg$-shell henceforth). The model assumes a closed $^{56}$Ni$_{28}$ core and does not allow for core breaking. The neutron single-particle energies of $2p_{3/2}, 1f_{5/2}, 2p_{1/2},$ and $1g_{9/2}$ in this $pfg$-shell region can be read from the low-lying states of $^{57}$Ni, because the low-lying states of $^{57}$Ni are well characterized as pure single-particle levels when $^{56}$Ni is a closed shell core. The adopted single-particle energies relative to the $2p_{3/2}$ are $\varepsilon_{p3/2} = 0.0$, $\varepsilon_{f5/2} = 0.77$, $\varepsilon_{p1/2} = 1.11$, and $\varepsilon_{g9/2} = 3.70$ in MeV \cite{19}. Since the above Hamiltonian is assumed to be an isospin-invariant, the proton single-particle energies are taken as the same values as the neutron single-particle energies. The force strengths of the extended $P + QQ$ interaction are taken so as to reproduce the energy levels of low-lying states in $^{64}$Ge as follows:

$$g_0 = 0.426(42/A), \quad g_2 = 0.274(42/A)^{5/3},$$

$$\chi_2 = \chi_2^{0}(42/A)^{5/3}/b^2 = 0.567(42/A)^{5/3}/b^2,$$

$$\chi_3 = \chi_3^{0}(42/A)^2/b^6 = 0.275(42/A)^2/b^6,$$

(2)

where $g_0$, $g_2$, $\chi_2$, and $\chi_3$ are the monopole pairing, quadrupole-pairing, $QQ$, and $OO$ force strengths, respectively. We adopt the harmonic-oscillator range parameter $b \sim A^{-1/3}$, the effective charge $e_p = 1.50e$ for proton and $e_n = 0.50e$ for neutron. We adjust phenomenologically force strengths of several monopole corrections so as to approximately reproduce the low-lying energy levels of $^{64}$Ge. These force strengths can also reproduce the low-lying energy levels of $^{58-66}$Ni, $^{60-64}$Zn, $^{66}$Ge, and $^{68}$Se.

In Fig. 1, calculated energy spectra are compared with experimental data for $^{64}$Ge. Two side bands are shown in addition to the ground-state band, i.e., positive-parity band on the band head $2^+$ and negative-parity band on the band head $3^-$. The calculations reproduce the observed three bands at good energies. The agreement between theory and experiment for the ground-state band up to spin $I = 8$ is good. The calculated $B(E2)$ value between the ground state and the first excited $I = 2^+$ state is $B(E2; 2^+ \rightarrow 0^-) = 245.3 \text{ e}^2\text{fm}^4$ corresponding to the quadrupole deformation $\beta \sim 0.2$. This value is consistent with the predictions of $\beta \sim 0.22$ by Möller and Nix \cite{20} and of $\beta \sim 0.22$ by Ennis et al. \cite{8}, and is comparable to the experimental data 12 W.u. of $^{66}$Ge nucleus.

The calculated occupation numbers of the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals in the ground-state band are 3.6, 3.2, 0.6, and 0.6 on the average, respectively. More than four nucleons are excited from the unperturbed configuration $(p_{3/2})^8$. The full $fp$ shell model calculation \cite{11} with the FPD6 interaction \cite{12} using the QMCD method has recently been performed for low-lying $I = 0^+, 2^+, 2^-$, and $4^+_1$ states of positive parity in $^{64}$Ge. The FPD6 calculation predicts the deformation $\beta_2 \sim 0.28$ which is somewhat larger than the other predictions $\beta_2 \sim 0.22$, and gives the triaxiality $\gamma \sim 27^\circ$ which is consistent with the others predictions. The FPD6 interaction seems too strong to yield appropriate collectivity \cite{12}, due to its drawback \cite{13}.

This can be seen from the occupation numbers of $f_{7/2}, p_{3/2}, f_{5/2},$ and $p_{1/2}$ which are 15.1, 2.6, 5.5, and 0.8, respectively. Two more nucleons are jumping to the orbitals above $p_{1/2}$ as compared with our result. The stronger collectivity caused by the FPD6 interaction is probably attributed to the mixture of the three orbitals $(f_{7/2}, p_{3/2},$ and $f_{5/2})$ due to the large matrix elements between $(f_{7/2}, p_{3/2})$ and $f_{5/2}$. This is the reason

FIG. 1. Comparison of experimental and calculated energy levels of $^{64}$Ge. The arrows designate $E2$ transitions with the calculated $B(E2)$ values indicated by their widths.
why \( B(E2; 2_1^+ \rightarrow 0_1^+) = 5 \times 10^2 (e^2\text{fm}^4) \) obtained in Ref. [10] is almost twice that of ours 245.3 (e^2\text{fm}^4).

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and its position lies in the deformed region but near the critical point. We can also see that the \( B(E2; 2_1^+ \rightarrow 2_1^+) \) value is large for \( \chi_2^0 > 0.45 \text{ MeV} \). This is consistent with the \( \gamma \) softness or the triaxiality discussed above.

This suggests that a phase transition occurs near the critical point \( \chi_{2\text{pn}}^0 \sim 0.35 \text{ MeV} \). The \( B(E2) \) value of the \( 2_2^+ \rightarrow 2_1^+ \) transition also becomes large for \( \chi_2^0 > 0.35 \text{ MeV} \), which results in the expected triaxiality \( \gamma \sim 26^\circ \) when \( \chi_{2\text{pn}}^0 = 0.567 \text{ MeV} \). Thus, the \( Q_pQ_n \) interaction plays an important role for the \( \gamma \) softness or the triaxiality in \( ^{64}\text{Ge} \).

Let us lastly study the negative-parity states as a function of the octupole force strength in Fig. 4. The other force strengths are fixed to those of Eq. (2). As mentioned above, the \( I = 3_{-1} \) state is very collective, and the excitation energy of the \( I = 3_{+1} \) state decreases as the octupole force strength increases until \( \chi_3^0 \sim 0.3 \text{ MeV} \), and increases as it goes beyond this point. The other negative-parity states have an insignificant dependence with respect to the force strength \( \chi_3^0 \) until the critical point, and increase for \( \chi_3^0 > 0.3 \). The ground-state energy is almost constant for \( 0 < \chi_{3\text{cr}}^0 < 0.3 \text{ MeV} \) and decreases quickly when going beyond this critical point. It seems that a phase transition occurs near the critical force strength \( \chi_{3\text{cr}}^0 \sim 0.3 \text{ MeV} \). The octupole force strength \( \chi_{3\text{cr}}^0 = 0.275 \text{ MeV} \) adopted in Fig. 1 is very close to the critical point \( \chi_{3\text{cr}}^0 \). Thus, \( ^{64}\text{Ge} \) seems to be near an octupole instability.

In summary, we have studied quadrupole and octupole correlations in the even-even \( N = Z \) nucleus \( ^{64}\text{Ge} \) by means of spherical shell model calculations. The \( P + QQ \) force model including octupole interaction and monopole corrections, which is schematic but realistic, is adopted for describing the quadrupole and octupole correlations. It is shown that \( ^{64}\text{Ge} \) is an unstable nucleus with respect to both the quadrupole and octupole deformations. The present results reveal that the \( p-n QQ \) interaction \( (Q_pQ_n) \) induces an onset of quadrupole deformation and \( \gamma \) softness. It can be expected to play an important role in the prolate-oblate shape coexistence of the neighboring even-even \( N = Z \) nucleus \( ^{66}\text{Se} \), which has been recently observed [22,23].

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FIG. 4. Excitation energies of the negative-parity states (in the upper figure) and the \( 0^+ \) ground-state energy (in the lower figure) as a function of the octupole force strength. The solid circles show the energies for the adopted force strength.

As mentioned earlier, it is very interesting to study roles of the proton-neutron part of the \( QQ \) force \( (Q_pQ_n) \). We make the study by varying the strength of \( Q_pQ_n \) \( (\chi_{2\text{pn}}^0) \) and keeping the other force strengths of Eq. (2). This is effective in seeing the dependence of quadrupole deformation on \( Q_pQ_n \), though the Hamiltonian without the isovector type of \( QQ \) interaction stops being isospin invariant. Figure 3 shows the excitation energies of the first and second \( 2^+ \) states and the \( B(E2) \) values as a function of \( \chi_{2\text{pn}}^0 \). The first \( I = 2_1^+ \) state is flat in energy with respect to the force strength \( \chi_{2\text{pn}}^0 \). However, the second excited \( I = 2_2^+ \) state strongly depends on \( \chi_{2\text{pn}}^0 \), and becomes lowest near \( \chi_{2\text{pn}}^0 \sim 0.35 \text{ MeV} \). In the isoscalar \( QQ \) force, \( \chi_{2\text{pn}}^0 \) is equal to the magnitude of proton-proton (\( pp \)) and neutron-neutron (\( nn \)) force strengths due to the isospin-invariance, i.e., \( \chi_{2\text{pn}}^0 = \chi_{2pp}^0 = \chi_{2nn}^0 \). The force strength \( \chi_{2\text{pn}}^0 = 0.567 \text{ MeV} \) which is adopted in Fig. 1 leads to the large \( B(E2) \) value \( B(E2; 2_1^+ \rightarrow 0_1^+) = 245.3 \text{ (e}^2\text{fm}^4 \) corresponding to the quadrupole deformation \( \beta \sim 0.2 \), as mentioned above. We can see, however, that \( B(E2; 2_1^+ \rightarrow 0_1^+) \) is very small for \( 0 < \chi_{2\text{pn}}^0 < 0.35 \text{ MeV} \).

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