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Soft octupole vibrations on superdeformed states in nuclei around ^{40}Ca suggested by Skyrme-HF and self-consistent RPA calculations

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Abstract. We present the results of fully self-consistent RPA calculation for low-frequency negative-parity modes built on superdeformed states in the ^{40}Ca region. The RPA calculation was carried out using the mixed representation on the three-dimensional Cartesian mesh in a box. The SD shell structure provides a very favorable situation for octupole shape fluctuations, and we show that the coherent excitation of protons and neutrons play an important role in the emergence of strongly collective octupole vibrations buit on the SD states in the $N = Z$ nuclei, ^{32}S, ^{36}Ar, ^{40}Ca and ^{44}Ti. In particular, the calculation suggests that a low-frequency, strongly collective $K^{\pi} = 1^{-}$ octupole vibration appears on the SD state in ^{40}Ca.

PACS. 21.60.-n Nuclear structure models and methods – 21.60.Jz Hartree-Fock and random-phase approximations

Properties of low-frequency vibrational modes are sensitive to details of shell structure near the Fermi energy. The superdeformed (SD) shell structure is drastically different from the normal deformed one; each major shell at the SD shape consists of about equal numbers of positive- and negative-parity levels. Thus, we expect soft octupole surface vibrational modes to emerge in SD nuclei. Various mean-field calculations [1,2,3] and quasiparticle RPA [4,5] on the basis of the rotating mean field (cranked shell model) indicate that SD nuclei are very soft against both axial and non-axial octupole deformations Accordingly, low-frequency octupole vibrations may appear near the SD yrast lines. In fact, such octupole vibrations have been discovered in heavy SD nuclei in the Hg-Pb region [6], and also in ^{152}Dy [7].

In recent years, the SD bands were discovered also in the ^{40}Ca region: ^{36}Ar [8], ^{40}Ca [9] and ^{44}Ti [10]. One of their important new features is that they are built on excited 0^{+} states and observed up to high spin, in contrast to the SD bands in heavier mass regions where their low-spin portions are unknown in almost all cases. Thus, in this SD region we can calculate vibrational modes built on superdeformed 0^{+} states and discuss their properties in the absence of rotational effects. Moreover, we can study coherent effects of proton and neutron excitations in these $N = Z$ nuclei. In a recent paper [11], we reported results of the symmetry-unrestricted Skyrme-Hartree-Fock (SHF) calculations for these SD bands.

Quite recently, Imagawa and Hashimoto [12,13] constructed a new computer code that carries out a self-consistent RPA in the mixed representation on the basis of the SHF mean field. In the mixed representation, particles are described in the coordinate representation, while holes are represented in the HF single-particle basis. This approach is fully self-consistent in that the same effective interction is used in both the mean field and the RPA calculations; *i.e.*, all terms of the Skyrme force are taken into account as the residual interactions for the RPA. Furthermore, in this method, we can treat strongly deformed nuclei on the same footing as spherical nuclei.

Figure 1 shows the low-frequency negative-parity intrinsic excitations on the SD states in ^{32}S, ^{36}Ar, ^{40}Ca, and ^{44}Ti, obtained by the mixed representation RPA calculation with the SkM* interaction. Although the SHF calculation yields small triaxiality for some of the SD states (see below), this calculation was done with the constraint $\gamma = 0$ for the mean fields. The RPA matrix was constructed using 30 and 50 mesh points in the

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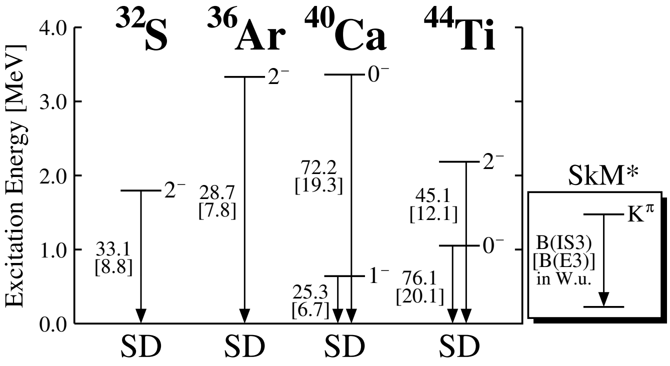

Fig. 1. Low-frequency negative-parity intrinsic excitations on the SD states in $N = Z$ nuclei around ^{40}Ca, obtained by means of the self-consistent RPA with SkM* interaction. Numbers beside the levels indicate the K quantum numbers.

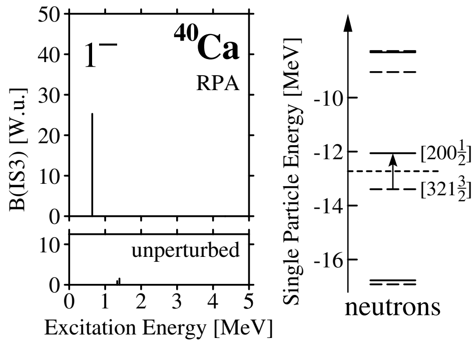

Fig. 2. Isoscalar octupole transition strengths and single-particle levels near the Fermi surface for the SD state in ^{40}Ca. Numbers in the right panel indicate the asymptotic quantum numbers $[Nn_3\Lambda\Omega]$. The solid (dashed) lines are used for positive- (negative-) parity single-particle levels. The dotted line indicates the Fermi surface.

direction of the minor and major axes, respectively, with the mesh size $h = 0.6$ fm. We obtained the spurious mode associated with the center of mass motion in the energy region lower than 0.1 MeV. Numbers beside the arrows (in parentheses) indicate the squared transition matrix elements for the mass (electric) octupole operators in the Weisskopf unit (W.u.). Since we are interested in collective vibrations, only the modes having mass octupole transition probabilities greater than 10 W.u. are plotted here. As displayed in fig. 1, we obtained in ^{40}Ca a low-frequency $K^\pi = 1^-$ mode possessing large octupole strength (26 W.u.) at 0.6 MeV above the SD band head. The RPA and the unperturbed isoscalar octupole transition strengths for the $K^\pi = 1^-$ intrinsic excitations are compared in fig. 2. The unperturbed strengths at excitation energies about 1.3–1.4 MeV are associated with the proton and the neutron excitations from the $[321\frac{3}{2}]$ state to the $[200\frac{1}{2}]$ state. The fact that the RPA strength is significantly enhanced in comparison with the unperturbed strength and the RPA energy is shifted down from the unperturbed particle-hole excitation energy indicates that this $K^\pi = 1^-$ mode possesses strong collectivity. In addition to this $K^\pi = 1^-$ mode, we obtained a number of axial and non-axial octupole vibrational modes buit on the SD states in the ^{40}Ca region: the $K^\pi = 2^-$ mode at 1.8 MeV in ^{32}S, the 2^- mode at 3.3 MeV in ^{36}Ar, the 0^- mode at 3.4 MeV in ^{40}Ca, the 0^- mode at 1.1 MeV and the 2^- mode at 2.2 MeV in ^{44}Ti. The RPA strengths of these modes are enhanced more than 10 times the unperturbed strengths. Also, the RPA excitation energies are shifted down by 0.8–1.5 MeV from the unperturbed particle-hole excitation energies.

In fact, the SD local minima for ^{40}Ca and ^{44}Ti obtained in the SHF mean-field calculation possess small triaxial deformations. Thus we also made the self-consistent RPA calculations taking into account the triaxial deformations. The results of this calculation were essentially the same as those presented in fig. 1, in which the axial symmetry constraint was imposed on the SD states, except that the $K^\pi \neq 0^-$ modes split into the doublets. We also made the SHF + RPA calculations using the SIII and SLy4 interactions, and obtained results similar to those obtained with the SKM* interaction.

Low-frequency collective octupole vibrational modes might mix with soft dipole modes in deformed unstable nuclei with neutron skins. Search for such a new kind of soft (dipole + octupole) vibrational modes of excitation in deformed unstable nuclei close to the neutron drip line is challenging both theoretically and experimentally.

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