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Microscopic structure of negative-parity vibrations built on superdeformed states in sulfur isotopes close to the neutron drip line

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Abstract. We study properties of the excitation modes built on the superdeformed states in sulfur isotopes close to the neutron drip line by means of the RPA based on the deformed Woods-Saxon potential in the coordinate mesh representation. We find that the low-lying state created by the excitation of a single neutron from a loosely bound low-Ω state to a high-Ω resonance state acquires an extremely strong octupole transition strength due to the spatially very extended structure of the particle-hole wave functions.

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New features, such as neutron skin and shell structure near the continuum, of unstable nuclei close to the neutron drip line are nowadays under lively discussions both theoretically and experimentally. Because properties of low-frequency excitation modes are quite sensitive to surface effects and details of shell structure, we expect that new kinds of excitations might emerge under such new situation of nuclear structure. We have been investigating such possibilities by means of the self-consistent RPA based on the Skyrme-Hartree-Fock (SHF) mean field. Although such RPA calculations for unstable nuclei are available (see, *e.g.*, refs. [1]), most of them are restricted to the case of spherical nuclei, and low-frequency RPA modes in deformed unstable nuclei remain largely unexplored. In order to clearly see the deformation effects, Inakura *et al.* investigated properties of negative-parity collective excitations built on superdeformed (SD) states in neutron-rich sulfur isotopes by means of the mixed representation RPA [2], and found many low-energy modes possessing strongly enhanced mass octupole transition strengths. This approach is fully self-consistent in that the same effective interaction is used in both the mean-field and RPA calculations. On the other hand, it is not easy in this method to identify microscopic particle-hole configurations generating individual RPA modes. Therefore, with the use of deformed Woods-Saxon potential and the conventional matrix formulation of the RPA, we have carried out a detailed analysis of microscopic structure of negative-parity excitation modes built on the SD states in the ^{50}S region. In this approach, we can easily obtain a simple and transparent understanding of the particle-hole configurations generating the RPA eigenmodes.

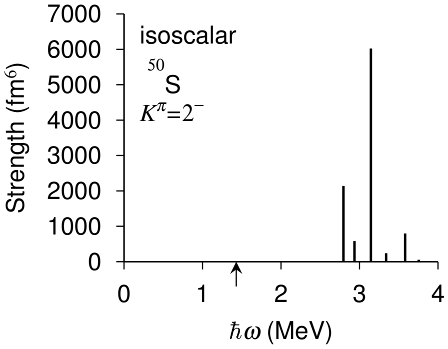

Fig. 1. Isoscalar octupole transition strengths for the SD state in ^{50}S close to the neutron drip line, obtained by the RPA calculation with $\beta_2 = 0.54$ and 0.73 for protons and neutrons, respectively, using the box of size $\rho_{\max} \times z_{\max} = 14.25$ fm $\times$ 22.0 fm. The arrow indicates the neutron threshold energy $E_{\rm th} = 1.43$ MeV.

In this paper, as a typical example, we concentrate on the result of calculation for the SD state in ^{50}S. According to the SHF calculation by Inakura *et al.* [3], this nucleus

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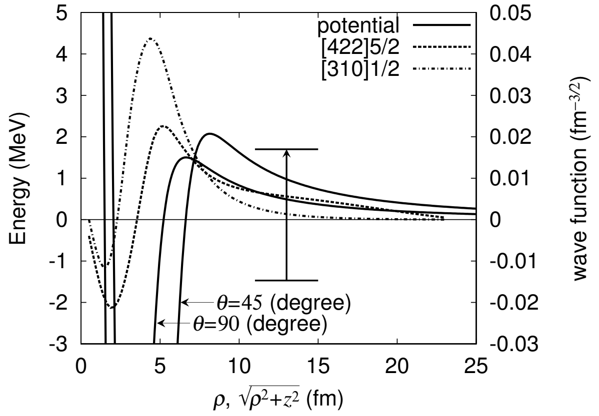

Fig. 2. The neutron particle-hole excitation contributing to the strongly enhanced octupole transition strength of the $K^\pi = 2^-$ state at 3.1 MeV. The *particle* and *hole* levels are labeled by the asymptotic quantum numbers $[Nn_3\Lambda]\Omega$. Their wave functions are drawn by the dotted and dash-dotted curves. The neutron single-particle potentials including the centrifugal barrier for $\Lambda = 2$ are plotted by solid curves; one as a function of ρ along the ρ-axis, and the other as a function of $\sqrt{\rho^2 + z^2}$ along the $\theta = 45°$ line.

is situated close to the neutron drip line, and we have chosen the deformation parameter β_2 of the SD state so as to approximately reproduce the single-particle spectrum near the Fermi surface obtained there. Figure 1 shows the isoscalar octupole transition strengths with $K^\pi = 2^-$. The highest peak at 3.1 MeV is associated with the excitation of a single neutron from the loosely bound [310]1/2 state to the resonance [422]5/2 state. We also obtain a peak of similar nature but with lower strength at 2.9 MeV, which is associated with the excitation of a single neutron from the loosely bound [431]3/2 state to the resonance [303]7/2 state. This difference in strength between the two peaks is understood from the asymptotic selection rule [4] valid for the lowest-energy particle-hole octupole excitations in the SD harmonic-oscillator potential; the former particle-hole excitation satisfies it whereas the latter does not. On the other hand, the second highest peak at 2.8 MeV is due to a neutron excitation from the loosely bound [431]3/2 state to a discretized continuum state with $\Omega^\pi = 1/2^-$. Therefore, its position and height do not have definite physical meanings.

The highest peak at 3.1 MeV has an extremely strong isoscalar octupole transition strength $B(Q^{\rm IS}3) \simeq 41$ W.u. and a weak electric transition strength $B(E3) \simeq 0.13$ W.u. (1 W.u. $\simeq 149$ fm^6 for ^{50}S). The wave functions of the major particle-hole configuration generating this RPA eigenmode are drawn in fig. 2. Because the [310]1/2 state is loosely bound and the [422]5/2 state is a resonance state, their wave functions are significantly extended outside of the half-density radius of this nucleus. This [422]5/2 state has an interesting property: Because the centrifugal barrier is angle dependent, it lies below the barrier for $\theta \le 60°$ while 0.2 MeV above along the ρ-axis ($\theta = 90°$). The resonance character of this state was confirmed by examining the box-size dependence of its energy and also by calculating the eigenphase sum following ref. [5]. It was also checked that this resonance state always exists for relevant values of β_2. We find that not only the resonance [422]5/2 state but also the weakly bound [310]1/2 state has a root-mean-square radius about 1 fm larger than the average value for neutrons. Together with the fact that this particle-hole configuration satisfies the asymptotic selection rule [4], the very extended spatial structures of their wave functions are the main reason why it has the extremely large transition strength. We plot in fig. 3 the spatial distributions of the strengths associated with individual particle-hole excitations,

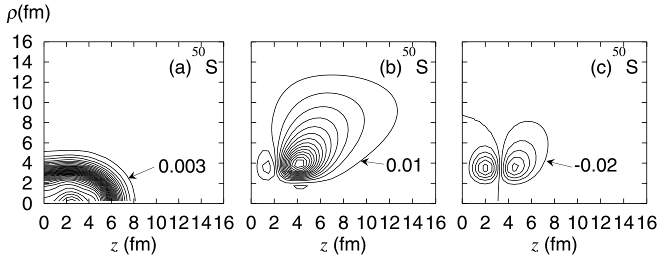

Fig. 3. (a) The neutron density distribution of the SD state in ^{50}S. The contour lines are drawn at intervals of 0.003 fm^{-3}. The neutron root-mean-square radius is $\sqrt{\langle r^2\rangle_{\rm n}} = 4.46$ fm. (b) The spatial distribution function $Q^{\rm ph}_{32}(\rho, z)$ of the octupole transition strength associated with the excitation of a single neutron from the loosely bound [310]1/2 state to the resonance [422]5/2 state on the SD state in ^{50}S. The contour lines are drawn at intervals of 0.02 fm. (c) The same as (b), but for the octupole excitation from the loosely bound [431]3/2 state to the resonance [303]7/2 state.

$$Q^{\rm ph}_{3K}(\rho, z) = \rho\phi_{\rm p}(\rho, z)Q_{3K}(\rho, z)\phi_{\rm h}(\rho, z), \qquad (1)$$

where $Q_{3K}(\rho, z) = r^3 Y_{3K} e^{-iK\varphi}$. It is clear that these particle-hole excitations have spatial distributions significantly extended outside of the nucleus. This spatially extended structure brings about the striking enhancement of the octupole transition strength, which may be regarded as one of the unique properties of excitation modes in nuclei close to the neutron drip line. Note that this mechanism of transition strength enhancement is different from the threshold effect associated with the excitation of a loosely bound neutron into the non-resonant continuum.

Other examples suggesting that this kind of enhancement phenomena is not restricted to the SD states will be presented elsewhere.

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