1. Introduction

The observed anomalous E2 properties in $^{32}$Mg and $^{30}$Ne, the large B(E2) values and the low excitation energies, are clear evidences of the vanishing of the N=20 shell closure. Several theoretical studies have shown the importance of the neutron 2p-2h configurations across the N=20 shell gap to describe these anomalous properties (e.g.,[3]). The 2p-2h configurations imply deformation of these nuclei, however, it is under great debate whether $^{32}$Mg is deformed or not. The observed energy ratios $E(4^+)/E(2^+)$ is 2.6 in $^{32}$Mg [4,5]. This value is in between the rigid rotor limit 3.3 and the vibrational limit 2.0. The B(E2) value (in single-particle units) is 15.0±2.5 in $^{32}$Mg, and this value is smaller than in deformed Mg isotopes (21.0±5.8 in $^{24}$Mg, 19.2±3.8 in $^{34}$Mg [6]). Moreover, in mean-field calculations, irrespective to relativistic or non-relativistic, the calculated ground states in $^{32}$Mg have been found to be spherical (e.g,[7]). Generally speaking, the neutron
2p-2h configurations can originate not only from deformation but also from neutron pairing correlations. In $^{32}$Mg these two effects may coexist and help to make the anomalous E2 properties. In the previous studies it is not clear which effect is more essential to describe the anomalous properties.

We have performed HFB plus QRPA calculations with Skyrme force for the first $2^+$ states in N=20 isotones. The QRPA equations are solved in coordinate space by using the Green’s function method. To emphasize the role of neutron pairing correlation, spherical symmetry is imposed. The residual interaction is consistently derived from the hamiltonian density of Skyrme force that has an explicit velocity dependence. A detailed account of the method can be found in Ref.[8]. We obtained a good agreement not only qualitatively but also quantitatively with the experimental results.

2. Ground state properties in N=20 isotones

The ground states are given by Skyrme-HFB calculations. The Skyrme parameter SkM* and the density-dependent pairing interaction, $V_{pair}(r, r') = V_{pair}[1 - \rho(r)/\rho_c]\delta(r - r')$, are adopted. $\rho_c = 0.16$ fm$^{-3}$ is fixed. The strength $V_{pair} = -418$ MeV·fm$^{-3}$ is determined so as to reproduce the experimental neutron pairing gap in $^{30}$Ne. The quasiparticle cut-off energy is taken to be $E_{cut} = 50$ MeV. Fig.1 shows the neutron single-particle levels in N=20 isotones calculated in HF. The size of the N=20 shell gaps change slowly, because $2d_{3/2}$ and $1f_{7/2}$ orbits have high centrifugal barriers. On the other hand, the calculated neutron pairing gaps change considerably from 1.26 MeV in $^{30}$Ne to zero in $^{38}$Ar (Fig.1). The mechanism can be understood by the change of the level density in the $fp$ shell. As close to
Figure 2. The $B(E2, 0^{+}_1 \rightarrow 2^{+}_1)$ transition probabilities and excitation energies of the first $2^+$ states in $N=20$ isotones calculated in QRPA with SkM*. For comparison the available experimental data [1,2] and the results of shell model [3] are shown.

Figure 3. The $B(E2, 0^{+}_1 \rightarrow 2^{+}_1)$ values and the excitation energies of the first $2^+$ states in $N=20$ isotones calculated with/without neutron pairing correlations. Proton pairing is included in both cases.

the neutron drip-line, the single-particle energy (SPE) of the high-$l$ orbit $1f_{7/2}$ change almost linearly while the changes of $2p_{3/2}$ and $2p_{1/2}$ SPEs become very slow. Moreover, the spin-orbit splitting of $2p_{3/2}$ and $2p_{1/2}$ states becomes smaller. Because of these different $l$-dependences of the SPEs, the level density in the $fp$ shell becomes higher in $^{32}$Mg and $^{30}$Ne. Within HFB calculations with spherical symmetry, the $N=20$ shell gap is naturally broken by neutron pairing correlations.

3. E2 properties in N=20 isotones

We have calculated the first $2^+$ states in N=20 isotones in HFB plus QRPA calculations with spherical symmetry. Our aim is to investigate whether
Figure 4. The proton and neutron transition probabilities $B(Q^2; 0^+ \rightarrow 2^+)$ in N=20 isotones, and the transition densities in $^{32}\text{Mg}$ calculated by QRPA with SkM*.

Figure 5. The excitation energy of the first $2^+$ state in $^{30}\text{Ne}$ as a function of $\rho_c$. The pairing strength is determined so as to get the experimental pairing gap $\Delta_n = 1.26$ MeV at each $\rho_c$. The limit $\rho_c = \infty$ corresponds to the volume-type pairing.

these $2^+$ states can be described as vibrational states built on the spherical ground states. In Fig.2 our QRPA results are compared with the available experimental data$^{1,2}$ and the results of shell model.$^3$ The QRPA calculations have been done with SkM* and the fixed pairing strength. The general properties of the first $2^+$ states in N=20 isotones, especially large quadrupole collectivity in $^{32}\text{Mg}$ and $^{30}\text{Ne}$, are well reproduced. Without neutron pairing correlations, we cannot explain the anomalous E2 properties (Fig.3). Under these considerations, we can conclude that the large quadrupole collectivity in $^{32}\text{Mg}$ and $^{30}\text{Ne}$ appears thanks to the neutron pairing correlations. To understand the mechanism that neutron pairing correlations help to make the large B(E2) values, we calculated the neutron transition probability $B(Q^2)$. If neutron pairing correlations exist, the $B(Q^2)$ value can be large and the surface of neutron density becomes soft (Fig.4). In this situation, at the first stage, an electric external field makes the proton density of the spherical ground state vibrate in small
amplitude. This proton vibration makes neutrons vibrate by coherence between protons and neutrons. This neutron vibration can be very large, because neutron density is very soft thanks to the neutron pairing correlations. Finally, this large neutron vibration makes protons vibrate again by coherence between protons and neutrons, and this proton vibration becomes very large. The transition density in $^{32}\text{Mg}$ clearly exhibits this situation that the proton and neutron densities vibrate altogether coherently (Fig.4). The peak position of the neutron transition density is slightly outside the nucleus due to the presence of neutron skin. We expect that the nature of this vibrational state is sensitive to the surface properties. Fig.5 shows the excitation energy of the first $2^+$ state in $^{30}\text{Ne}$ as a function of $\rho_c$. This state is very sensitive to $\rho_c$, and $\rho_c = 0.16 \text{ fm}^{-3}$ gives $E_{2^+} = 0.64 \text{ MeV}$ that is close to the experimental observation $0.791(26) \text{ MeV}$. The information of low-lying collective states in neutron-rich nuclei may help to pin down the density dependence of pairing interactions.

4. Conclusions

We have studied the first $2^+$ states in $N=20$ isotones by the HFB plus QRPA with Skyrme force. Because of the different behaviors of the neutron $1f$ and $2p$ orbits around zero energy, the neutron pairing correlations appear. This mechanism breaks the $N=20$ magicity in $^{32}\text{Mg}$ and $^{30}\text{Ne}$. Within QRPA calculations with spherical symmetry, the $B(E2)$ values and the excitation energies of the first $2^+$ states in $N=20$ isotones including $^{32}\text{Mg}$ and $^{30}\text{Ne}$ are well described. The existing experimental data are reproduced quantitatively. The important role of the neutron pairing correlations is emphasized. In the real $^{32}\text{Mg}$ nucleus, both neutron pairing and deformation effects may coexist and help to make the large $B(E2)$ value, but our calculation shows that neutron pairing correlations are essential.

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