Di-neutron correlation in monopole pair transfer modes near the neutron-separation energy in Sn, Ni, Ca, Zr isotopes

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Abstract. We discuss the monopole pair transfer by means of the Hartree-Fock-Bogoliubov method and the continuum quasiparticle random phase approximation. We investigate the low-lying pair-vibrational state and the pair-rotational ground state having small separation energy in neutron-rich Sn isotopes and Ni, Zr and Ca isotopes. We show that the transfer amplitudes of the $0^+$ states are characterized by the coherent superposition of two-quasiparticle configurations up to high orbital angular momenta $l \sim 12$. It suggests the transfer motion of a di-neutron.

1. Introduction

The neutron-rich nuclei have anomalous features, for instance, the low density distributions outside the nuclear surface such as neutron-halo and -skin, which are not seen in stable nuclei. In such a situation the di-neutron correlation is expected [1-4] because the pairing in low-density neutron matter is predicted to be stronger [5, 6]. If the neutron pairing becomes strong around the surface we may expect a large probability for a neutron pair to be added or removed from a nucleus [7-9].

In this work, we discuss the relation between the di-neutron correlation and the characteristic $0^+$ states, i.e. the ground state and the pair-addition vibrational state in neutron-rich nuclei. To clarify the di-neutron behavior we analyze the microscopic structure of the pair-transfer transition densities.

2. Two-neutron transfer to the weakly bound $0^+$ states

We have studied two-neutron transfer modes populating low-lying $0^+$ states and the ground states in even-even Sn, Zr, Ni and Ca isotopes. We use Skyrme-Hartree-Fock-Bogoliubov mean-field model and the continuum quasiparticle random phase approximation (continuum QRPA) theory [4]. The two-neutron transfer strength connecting the ground states is enhanced in the very neutron-rich regions (see Fig. 1(a)). In the case of the neutron-rich Sn isotopes, the strength of the ground state transfer is significantly enhanced above $A=140$ [8, 9]. Also the pair-vibrational $0^+_2$ states with anomalously large pair-additional strength appear in the Sn isotopes with $A=132-140$ [8].

We first analyze microscopic structure of these low-lying pair vibrational states in $^{132-140}$Sn. Within the QRPA theory, one can characterize an excitation mode in terms of the forward-
characters are also seen in the pair vibrational state in $A_{total}$ although the sum of the probabilities of the five components is about $91\%$. Other superposition of the five transition densities can reproduce only approximately half of the $fm$. Its amplitude in external part is small comparing with the total transition density. The significantly larger than the other four, but amplitudes of the five transition densities $|\alpha l, ii tr \rangle$. The thick dashed curve is the sum of the five components.

and backward-going amplitudes $X_{nlj}^\nu$ and $Y_{nlj}^\nu*$ associated with the creation and the annihilation of two-quasiparticle configurations $|ii l \rangle = (nlj) (n^l l')$. Similarly, the transition density $\rho_{ll l}^\nu(r)$ for the pair transfer operator can be decomposed as $\rho_{ll l}^\nu(r) = \sum_{ii} \rho_{ll l, ii}^\nu(r)$ in terms of the two-quasiparticle configurations. The component of the transition density $\rho_{ll l, ii}^\nu(r)$ is expressed using $X_{nlj}^\nu$ and $Y_{nlj}^\nu*$ as

$$\rho_{ll l, ii}^\nu(r) = (-)^l X_{nlj}^\nu (l l') Y_{nlj}^\nu* \left( 0 | \rho_{\alpha} (r) | ii l \right) + (-)^l Y_{nlj}^\nu (l l') X_{nlj}^\nu* \left( ii l | \rho_{\alpha} (r) | 0 \right). \quad (1)$$

Fig. 1(b) shows the transition density of the anomalous $0^+ \ _{134}^\nu$ states in $^{134}_{2}^\nu$. Decomposed transition densities $\rho_{ll l, ii}^\nu(r)$ are also plotted for dominant five two-quasiparticle configurations $[3p_{3/2}]^2$, $[1h_{9/2}]^2$, $[2f_{5/2}]^2$, $[2f_{7/2}]^2$ and $[1i_{13/2}]^2$, which have the largest probabilities $|X_{nlj}^\nu|^2 - |Y_{nlj}^\nu|^2 = 0.565, 0.136, 0.087, 0.078$ and 0.058, respectively. The probability of $[3p_{3/2}]^2$ is significantly larger than the other four, but amplitudes of the five transition densities are comparable as seen in Fig. 1(b). It suggests that the $0^+ \ _{134}^\nu$ state has a certain degree of collectivity.

It is seen in Fig. 1(b) that the $[3p_{3/2}]^2$ component has an extended tail reaching $r \sim 15 \ fm$. Its amplitude in external part is small comparing with the total transition density. The superposition of the five transition densities can reproduce only approximately half of the total although the sum of the probabilities of the five components is about $91\%$. Other configurations play an important role to construct the pair vibrational state in $^{134}_{2}^\nu$. These characters are also seen in the pair vibrational state in $A=132\sim 140$ isotopes.

To investigate the behavior of all the two-quasiparticle configurations, we plot in Fig. 2(a) the transition density decomposed with respect to the orbital angular momentum of the quasiparticle states contributing to the phonon amplitude $X_{nlj}^\nu$ and $Y_{nlj}^\nu*$. The largest occupied orbital angular momentum is $l_{occ} = 5(1h_{11/2})$ in the ground state of $^{134}_{2}^\nu$.

Although the amplitude $(X_{nlj}^\nu)$ of each high-$l$ component is very small, the superposition of these small transition densities reproduces the total transition density in Fig. 2(a). The accumulating coherent high-$l$ contributions in the pair-vibrational state suggests the di-neutron correlation discussed in the same way in Ref.[3, 4]. The high-$l$ two-quasiparticle configurations $l > l_{occ}$ are seen outside the nuclear surface in Fig. 2(a).

Figure 1. (a) The two-neutron transfer strengths populating the ground states for $Sn(A=100-150)$, $Zr(A=80-140)$, $Ni(A=56-88)$ and $Ca(A=36-70)$ isotopes, plotted with circles, and the pair-addition strengths of the low-lying pair vibrational state, plotted with diamonds. Adopted Sklyrme parameter is SLy4 for $Sn$ and $Ni$ isotopes, and SkH4 for $Zr$ and $Ca$ isotopes. (b) The pair-addition transition density $\rho_{ll l}^\nu(r)$ of the low-lying pair vibration in $^{134}_{2}^\nu$ and its dominant five components $\rho_{ll l, ii}^\nu(r)$. The thick dashed curve is the sum of the five components.

Figure 2. The two-neutron transfer strengths populating the ground states for $Sn(A=100-150)$, $Zr(A=80-140)$, $Ni(A=56-88)$ and $Ca(A=36-70)$ isotopes, plotted with circles, and the pair-addition strengths of the low-lying pair vibrational state, plotted with diamonds. Adopted Sklyrme parameter is SLy4 for $Sn$ and $Ni$ isotopes, and SkH4 for $Zr$ and $Ca$ isotopes. (b) The pair-addition transition density $\rho_{ll l}^\nu(r)$ of the low-lying pair vibration in $^{134}_{2}^\nu$ and its dominant five components $\rho_{ll l, ii}^\nu(r)$. The thick dashed curve is the sum of the five components.
Figure 2. (a) Decomposition of the pair-addition transition density of the low-lying pair vibrational state in $^{134}$Sn with respect to the orbital angular momentum cutoff $l_{\text{cut}}=0, 1, 2, \cdots, 12$. (b) The same as (a) but for the ground state transfer in $^{142}$Sn.

Fig. 2(b) shows the transition density for the transfer to the ground state in $^{142}$Sn. We also found that the weakly bound $3p_3/2$ orbit and unbound orbits in continuum contribute to the ground state of $N > 90$ Sn isotopes. Comparing Figs. 2(a) with 2(b) we find that the pair vibrational state in $^{134}$Sn and the ground state transfer in $^{142}$Sn have similar characters: the extended tail and the accumulating high-$l$ contribution.

We have also studied the Ni, Zr and Ca isotopes in order to explore whether the di-neutron correlation appears systematically. The strengths of the ground state transfer are significantly enhanced in $N > 40$ for Ca, $N > 56$ for Ni, and $N \geq 82$ for Zr isotopes. These nuclei have the extended pair density $\tilde{\rho}(r)$ and the di-neutron behavior like Fig. 2(b).

We have also examined the di-neutron character in the low-lying $0^+$ states in neutron-rich Ca, Ni and Zr isotopes. The low-lying pair vibrational state appears only in Ni isotopes with $A=78-84$. The pair vibrational states in $^{78-84}$Ni and the ground state transfer in $^{86-88}$Ni have the similar di-neutron character.

3. Conclusion

We find that two-quasiparticle configurations involving continuum states up to around $l \sim 12$ accumulate coherently to form the total transition density of the pair-vibrational $0^+_2$ state in $^{132-140}$Sn. It suggests that the pair vibrational state is characterized by the motion of a di-neutron. The large ground state transfer in very neutron-rich isotopes is also characterized by the di-neutron behavior.

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