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Di-neutron correlation in asymptotic tail of weakly bound nuclei

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Neutrons penetrating far outside the nuclear surface often exhibit exotic features of neutron-rich nuclei close to the drip-line. An important question is whether and how neutrons are correlated in the external tail region. The di-neutron correlation in two-neutron halo nuclei, such as ^{11}Li, has attracted attention in this context.[1,2] However, theoretical analyses using the Hartree-Fock-Bogoliubov (HFB) models suggest that the di-neutron correlation also prevails in heavier mass nuclei, including nuclei close to the stability line.[3,4] In the present work, we attempt to clarify the emergence mechanism of the di-neutron correlation by investigating the Cooper pair wave function in the Skyrme HFB model both numerically and analytically, with a focus on its asymptotic behavior at large distances.

We have performed a systematic Skyrme HFB calculation[5] for even-even Ca, Ni, Zr, and Sn isotopes ranging from the stability line to the neutron drip-line. In order to guarantee convergence at large distances, we solve the HFB equation in the radial coordinate representation, using a very large radial cut-off at 100 fm and the orbital angular momentum cut-off at $l = 72$. We then evaluate the neutron pair condensate (equivalent to the pair density and the pairing tensor) $\tilde{\rho}(\boldsymbol{R}) \equiv \langle\Phi_0|\psi(\boldsymbol{R}\uparrow)\psi(\boldsymbol{R}\downarrow)|\Phi_0\rangle = \Psi_{\rm pair}(\boldsymbol{R},\boldsymbol{R})$. Note that the pair condensate is a part of the neutron Cooper pair wave function, defined by $\Psi_{\rm pair}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \langle\Phi_0|\psi(\boldsymbol{r}_1\uparrow)\psi(\boldsymbol{r}_2\downarrow)|\Phi_0\rangle$.

The asymptotics of the pair condensate is characterized by an exponential behavior $\tilde{\rho}(R) \to C\exp(-\tilde{\kappa}R)$, and the exponential constant $\tilde{\kappa}$ is extracted by a fitting to the microscopically calculated $\tilde{\rho}(R)$. As shown in Fig. 1, the extracted exponential constants (solid symbols) follow a universal relation $\tilde{\kappa} = \sqrt{8m|\lambda|}/\hbar$, where λ is the Fermi energy and m is the neutron mass. The result is different from the previous estimate [6,7] $\tilde{\kappa}_{\rm qp} = \sqrt{2m(|\lambda|+E_{\rm qp,l})}/\hbar + \sqrt{2m(|\lambda|-E_{\rm qp,l})}/\hbar$ (open symbols), which relies on the asymptotic behavior of the quasiparticle wave function with the lowest quasiparticle energy $E_{\rm qp,l}$.

The universal relation can be interpreted as the penetration of a di-neutron with mass $M = 2m$ and with the binding energy given by the two-neutron separation energy $S_{2n} = 2|\lambda|$, i.e. $\tilde{\kappa} = \sqrt{2MS_{2n}}/\hbar$. We can justify this interpretation via an analytic and general examination of the HFB theory. It should be noted that in the limit $r_1, r_2 \to \infty$, the following two-particle Schroedinger equation holds for the Cooper pair wave function:

$$(t(1)+t(2)+v(1,2))\Psi_{\rm pair}(\boldsymbol{r}_1,\boldsymbol{r}_2) = 2\lambda\Psi_{\rm pair}(\boldsymbol{r}_1,\boldsymbol{r}_2) \quad (1)$$

where $v(1,2)$ is the nn interaction. As a consequence, the asymptotic form is given in terms of the di-neutron coordinate system $r = |\boldsymbol{r}_1 - \boldsymbol{r}_2|, R = |(\boldsymbol{r}_1+\boldsymbol{r}_2)/2|$ as

$$\Psi_{\rm pair}(\boldsymbol{r}_1,\boldsymbol{r}_2) \to C_0^{L=0}\phi_0^{L=0}(r)\exp(-\kappa_{\rm d}R)/R \quad (2)$$

for small r. Here, $\phi_0^{L=0}(r)$ is the wave function of the S-wave virtual state of the nn system, representing the di-neutron, and the exponential constant $\kappa_{\rm d} = \sqrt{2M(2|\lambda|)}/\hbar$ arising from the center of mass motion of the di-neutron.

We also found that the di-neutron asymptotics, Eq.(2), dominates in weakly bound neutron-rich nuclei with a small neutron separation energy or small $|\lambda|$. Conversely, single-particle (quasiparticle) components also contribute to the asymptotics of the Cooper pair in nuclei having a larger neutron separation energy, as the single-particle value (open symbol) and the full value (solid one) coincide in these nuclei. As a corollary, the condition for the dominance of the di-neutron correlation is given as $|\lambda| \lesssim \Delta$ or $S_{2n} \lesssim 2\Delta$.

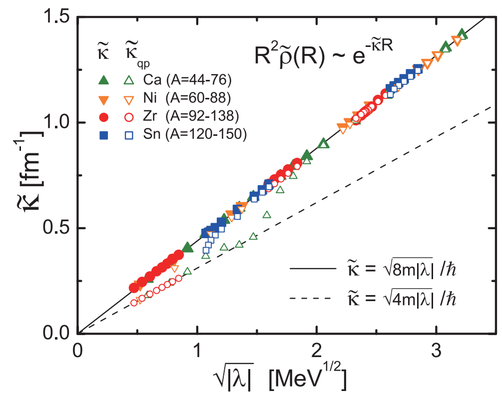

Fig. 1. The asymptotic exponential constant $\tilde{\kappa}$ of the neutron pair condensate $\tilde{\rho}(R)$.

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