Eur. Phys. J. A **25**, s01, 563–565 (2005)
DOI: 10.1140/epjad/i2005-06-045-9

EPJ A direct
electronic only

Di-neutron correlations in medium-mass neutron-rich nuclei near the dripline

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Received: 21 October 2004 /
Published online: 29 June 2005 – © Società Italiana di Fisica / Springer-Verlag 2005

Abstract. On the basis of the coordinate-space Hartree-Fock-Bogoliubov and the continuum quasiparticle random phase approximation (QRPA) theories, we demonstrate that a di-neutron correlation exists in the ground states of medium-mass neutron-rich nuclei near the dripline, and we suggest that the soft dipole excitation has the character of di-neutron motion against the remaining $A-2$ subsystem.

PACS. 21.60.Jz Hartree-Fock and random-phase approximations

Pairing among like nucleons is one of the most important many-body correlations in nuclei, influencing strongly properties of low-lying excitations and the ground state. This is true not only in stable nuclei but also in neutron-rich nuclei near the drip-line where weak binding of the last neutrons may cause further characteristic behaviors. Indeed in light two-neutron halo nuclei, *e.g.* in ^{11}Li, the existence of spatial correlation among the halo neutrons at short relative distances —the di-neutron correlation— is predicted [1,2,3]. In the present work, we generalize the concept of the di-neutron correlation in heavier near-dripline systems, in particular in the medium-mass region, where, although the halo may not develop significantly, many-body coherency can be expected due to the presence of more than two valence neutrons. Here we look into not only the ground state but also the soft dipole excitation whose observation is recently extended up to the oxygen isotopes [4]. We have performed theoretical investigations for even-even $^{18-24}$O, $^{50-58}$Ca and $^{80-86}$Ni. Although we here present figures only for ^{84}Ni, essentially the same results are obtained for the other isotopes and nuclides [5].

Our description of the correlated ground state is based on the formalism of the standard coordinate-space Hartree-Fock-Bogoliubov (HFB) theory [6], In the numerical calculation we adopt the mixed-type density-dependent delta-force as the effective pairing interaction [6], and a Woods-Saxon potential for the particle-hole mean field. The spatial behavior of correlated neutron pairs in the ground state $|\Phi_0\rangle$ can be displayed by

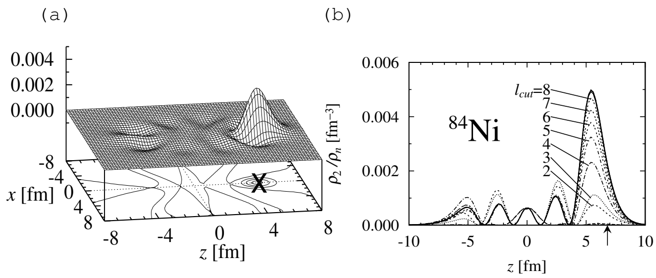

Fig. 1. (a) Neutron two-body correlation density $\rho_2(\boldsymbol{r}\uparrow,\boldsymbol{r}'\downarrow)/\rho_n(\boldsymbol{r}'\downarrow)$ in the ground state of ^{84}Ni, plotted as a function $\boldsymbol{r}$ on the xz plane. Here the position $\boldsymbol{r}'$ of one reference neutron is fixed at the surface along the z-axis (at the radius $R_{\rm surf}=4.8\,$fm, marked by X). (b) The same quantity but along the z-axis, and the reference neutron is fixed at the exterior position $R_{\rm surf}+2\,$fm marked by the arrow. Here the results obtained by neglecting high-l quasineutron orbits with the cut-off $l_{\rm cut}$ are also shown.

means of the two-body correlation density:

$$\rho_2(\boldsymbol{r}\uparrow,\boldsymbol{r}'\downarrow)=\langle\Phi_0|\sum_{i\neq j\in n}\delta(\boldsymbol{r}-\boldsymbol{r}_i)\delta(\boldsymbol{r}'-\boldsymbol{r}_j)\delta_{\sigma_i\uparrow}\delta_{\sigma_j\downarrow}|\Phi_0\rangle -\rho_n(\boldsymbol{r}\uparrow)\rho_n(\boldsymbol{r}'\downarrow). \quad (1)$$

It probes the probability distribution of the pair wave function as $\rho_2\approx|\langle\Phi_0|\psi_n^\dagger(\boldsymbol{r}\uparrow)\psi_n^\dagger(\boldsymbol{r}'\downarrow)|\Phi_0\rangle|^2$, where $\psi_q^\dagger(\boldsymbol{r}\sigma)$ is the nucleon creation operator ($q=np,\ \sigma=\uparrow\downarrow$).

Figure 1 displays the apparent presence of the di-neutron correlation in the ground state. Two neutrons with anti-parallel spins are correlated strongly at short relative distances $|\boldsymbol{r}-\boldsymbol{r}'|\lesssim 2$–$3\,$fm, where about a half

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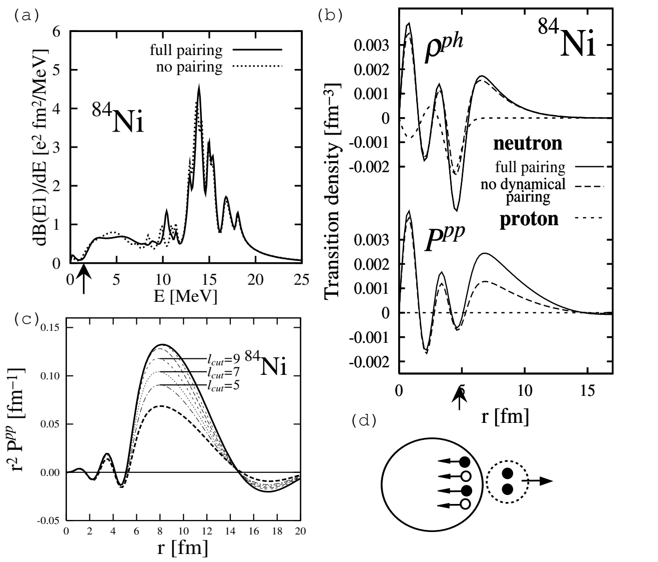

Fig. 2. (a) The calculated $E1$ strength function in ^{84}Ni. The threshold for neutron escaping is shown by the arrow. (b) The particle-hole $\rho^{\mathrm{ph}}(r)$ and the particle-pair $P^{\mathrm{pp}}(r)$ transition densities for the soft dipole excitation evaluated at $E = 4\,\mathrm{MeV}$ in ^{84}Ni. The influence of the neutron pair correlation on $P^{\mathrm{pp}}(r)$ is large as shown by the result (dashed line) neglecting the dynamical pair correlation. (c) The particle-pair transition density $r^2P^{\mathrm{pp}}(r)$ showing contributions of high-l quasiparticle states. The thick dashed line is obtained without the dynamical pair correlation. (d) A schematic drawing of the di-neutron picture.

in the probability distribution of the pair is concentrated for a fixed $\boldsymbol{r}'$. The localization is clearly seen also in the composition of the two-body correlation density with respect to the contributions of quasiparticle orbits involved; the quasiparticle states having large orbital angular momenta $l \sim$ 4–8 (about twice the maximum angular momenta of the bound orbits) contribute coherently to form the di-neutron correlation (fig. 1(b)). This is in accord with a relation $r_d \sim 2R/l_{\max}$ between the size of localization r_d and the maximum angular momentum $l_{\max}$ (R being the distance from the origin to the center of mass of the di-neutron), which can be expected from the general uncertainty relation. It is found that the di-neutron correlation becomes strong at the surface and the skin regions although it prevails also inside the nuclear volume. The spatial correlation of the di-neutron type is generally seen also in more stable nuclei. In nuclei near the dripline, however, the pair correlation is more significant in the low-density skin region than in the external region of stable nuclei because the density-dependent pair force acts stronger on the neutrons there.

The above observations suggest that the di-neutron correlation may be probed in characteristic surface excitation modes of near-dripline nuclei. Here we seek such possibility in connection with the soft isovector dipole mode. For this purpose, we describe the excitation by means of the recently developed continuum quasiparticle random phase approximation (the continuum QRPA) [7]. It is based on a time dependent extension of the coordinate-space HFB, describing a correlated response of a nucleus against an external field (the electric dipole field). Importantly, it takes into account escaping process of neutrons. As the soft dipole excitation often lies above the threshold, precise treatments of the neutron continuum states are necessary. The continuum QRPA facilitates such a description in a microscopic way, and takes into account the pair correlation in the continuum excited state, *i.e.*, the correlation among two escaping neutrons.

Figure 2(a) exhibits the presence of the soft dipole excitation in the calculated $E1$ strength function. We also plot in fig. 2(b) the particle-hole $\rho^{\mathrm{ph}}(r)$ and the particle-pair $P^{\mathrm{pp}}(r)$ transition densities for this mode, defined respectively by

$$\rho^{\mathrm{ph}}_{iq}(\boldsymbol{r}) = \langle \Phi_i | \sum_{\sigma} \psi^{\dagger}_q(\boldsymbol{r}\sigma)\psi_q(\boldsymbol{r}\sigma) \, |\Phi_0\rangle \,, \tag{2}$$

$$P^{\mathrm{pp}}_{iq}(\boldsymbol{r}) = \langle \Phi_i | \, \psi^{\dagger}_q(\boldsymbol{r}\uparrow)\psi^{\dagger}_q(\boldsymbol{r}\downarrow) \, |\Phi_0\rangle \,. \tag{3}$$

The latter describes how neutron pairs in an anti-parallel spin configuration move in the excited state $|\Phi_i\rangle$. The calculation (fig. 2(b)) shows that the transition amplitude for the particle-particle channel $P^{\mathrm{pp}}(r)$ dominates over the particle-hole amplitude $\rho^{\mathrm{ph}}(r)$ in the external region $r \gtrsim 5\,\mathrm{fm}$. Further, a strong enhancement of the neutron-pair transition amplitude $P^{\mathrm{pp}}(r)$ by about a factor of two is caused by a dynamical pair correlation acting among moving neutrons in the excited state (fig. 2(b)). This indicates that the soft dipole excitation is not a simple uncorrelated excitation of one neutron from a bound orbit to continuum states near the threshold. It is rather the motion of two correlated neutrons in the exterior region.

To clarify the nature of the correlation, we decomposed the transition densities with respect to the orbital angular momenta of quasineutron orbits contributing to the soft dipole excitation. It is found that the large enhancement in $P^{\mathrm{pp}}(r)$ originates from a coherent superposition of two-quasiparticle configurations $[l \times (l+1)]_{L=1}$ consisting of continuum quasiparticle orbits with high orbital angular momenta l reaching around $l \sim 10$ (fig. 2(c)). The coherent contribution of high-l orbits is in accord with the similar high-l contributions to the di-neutron behavior in the two-body correlation density of the ground state (fig. 1(b)): it may be deduced that the large enhancement of neutron pair transition density $P^{\mathrm{pp}}(r)$ has the same origin. This observation susggests that the soft dipole excitation is characterized by the motion of a di-neutron in the nuclear exterior against the remaining $A-2$ subsystem (fig. 2(d)).

This work was supported by the Grant-in-Aid for Scientific Research (No. 14540250) from the Japan Society for the Promotion of Science.

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