Structure of few-alpha systems in cold neutron matter[†]

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The first 0^+ excited state of ^{12}C, the Hoyle state,[1)] is important for generating ^{12}C elements in the triple alpha (^{4}He nucleus) reaction via the resonant ground state of ^{8}Be, where alpha clusters are well developed. An accurate description of such alpha-induced reactions in the astrophysical environment, such as core-collapse supernovae and neutron star mergers, is required.[2)] Recently, the quasiparticle properties of an alpha particle in dilute cold neutron matter have been discussed in terms of a Fermi polaron,[3)] where an alpha particle is treated as an impurity in majority neutron matter. In the polaron picture, the effective mass of the alpha particle depends on the density of neutron matter. We introduce medium-induced two- and three-alpha interactions considering simple Feynman diagrams wherein few-alpha particles exchange momenta.

This study investigates two- and three-alpha systems in dilute neutron matter at zero temperature by precisely solving a few-alpha problem, including the quasiparticle properties of an alpha particle. We consider the density of neutron matter up to 1/100th of the saturation density, $\rho_0 \sim 0.16$ fm^{-3}, which corresponds to the Fermi momentum, $k_F \sim 0.360$ fm^{-1}. We discuss the possible stability and structure changes in the Hoyle state and ground state of ^{8}Be.

The effective Hamiltonian for two- and three-alpha systems is given by:

$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2M^*} - T_{\rm cm} + \sum_{i>j}\left(V_{\alpha\alpha,ij} + V^{(2)}_{{\rm eff},ij}\right) + V_{\alpha\alpha\alpha} + V^{(3)}_{\rm eff},$$

where M^* is the effective mass of alpha particles, $\boldsymbol{p}_i$ is the momentum operator of the ith alpha particle, and $T_{\rm cm}$ is the center-of-mass kinetic energy: moreover, $V_{\alpha\alpha}$ and $V_{\alpha\alpha\alpha}$ are the direct two- and three-alpha interactions, while $V^{(2)}_{\rm eff}$ and $V^{(3)}_{\rm eff}$ are the medium-induced two- and three-alpha interactions, respectively. Note that $V_{\alpha\alpha}$ is deep and has forbidden states owing to the Pauli principle. The physical constants and further calculation settings are given in Refs. 4) and 5). The wave function of the few-alpha system can be expressed by superpositioning the correlated Gaussian basis functions, whose parameters are obtained by the stochastic variational method.[6)]

Figure 1 shows the in-medium energies and root-mean-square (rms) pair distance of the Hoyle state, labeled C*, and the ground state of ^{8}Be as functions of the Fermi momentum of background neutron matter. The energies of the Hoyle state and ^{8}Be decreased for larger values of k_F owing to the short-range attractive medium-induced two-alpha interaction. Eventually, ^{8}Be and the Hoyle state were bound in neutron matter with $k_F \geq 0.08$ fm^{-1} and 0.16 fm^{-1} corresponding to $\approx 10^{-4}\rho_0$ and $10^{-3}\rho_0$, respectively. Moreover, in terms of structural change, it can be observed that the size of the Hoyle state and ^{8}Be decreased. The rms pair distance monotonically decreased for larger k_F because the internal amplitude of wave functions was strongly modified by the medium-induced interactions. Notably, the shrinkage is consistent with the study investigating the finite system, *i.e.*, the $\alpha-\alpha-n$ cluster system.[7)]

Thus, we point out the possible stability of fundamental light nuclear ingredients, the Hoyle state, and ^{8}Be. This could significantly impact the modeling of stellar collapse and neutron star mergers, as well as relevant nucleosynthesis.

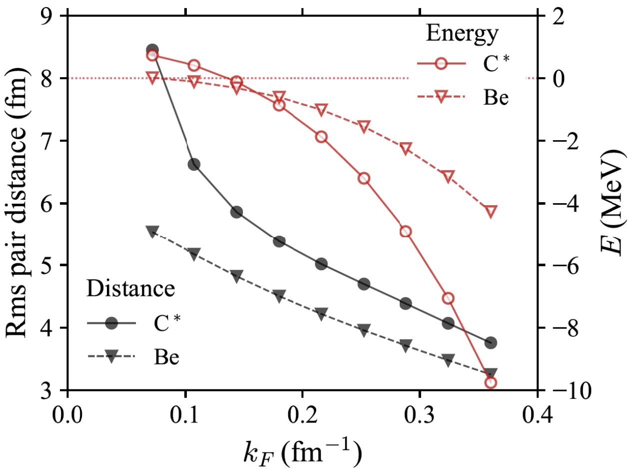

Fig. 1. Energies measured from two- and three-alpha threshold, E (right-hand scale) and rms pair distance (left-hand scale) of the Hoyle state, and ground state of ^{8}Be as functions of the neutron medium Fermi momentum, k_F. The dotted line indicates $E = 0$ MeV.

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† Condensed from Phys. Rev. C **104**, 065801 (2021)
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