Evidence for three-particle correlations in nuclear matter†

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The properties of infinite nuclear matter have been the subject of intensive investigations for many decades, mainly because of the wide range of applications, including the properties of heavy nuclei, supernova explosions, and neutron stars. In particular, studies on three-particle correlations have a long history, beginning with the pioneering work of Bethe in 1965.[1)] In this paper we focus our attention on the skewness of nuclear matter and its implications for three-particle correlations. Skewness is defined as $J = 27\rho^3 \left(\mathrm{d}^3 E_{\mathrm{A}}/\mathrm{d}\rho^3\right)$ at $\rho = \rho_0$, where E_{A} is the energy per nucleon in isospin symmetric nuclear matter, and ρ_0 is the saturation density. Recently, empirical values of J have been extracted in Ref. 2) from heavy ion collisions and neutron star observations, and the following range was deduced:

$$-0.50\ \mathrm{GeV} < J < -0.01\ \mathrm{GeV}\,. \tag{1}$$

By using the theoretical framework of the Landau-Migdal theory, we will show that those empirical values provide us with information on three-particle correlations in nuclear matter.

Extending Landau's basic formula[3)] for the variation of the energy density of nuclear matter to include the third order term, which involves the totally symmetric spin-isospin averaged three-particle forward scattering amplitude $h(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)$, we are able to derive the following exact expression for J:

$$J = -9K + \frac{9p_F^2}{M^{*2}} \times \left(-\frac{1}{3} + 3\frac{M - M^*}{M} - \frac{4}{3}\frac{p_F}{M^*}\frac{\mathrm{d}M^*}{\mathrm{d}p_F} + (H_0 - H_1)\right), \tag{2}$$

where K is the incompressibility, p_F the Fermi momentum, $M^* \equiv M^*(k = p_F)$ the Landau effective mass at the Fermi surface, $\frac{\mathrm{d}M^*}{\mathrm{d}p_F} = \frac{\mathrm{d}M^*(k)}{\mathrm{d}k}|_{k=p_F}$ the slope of $M^*(k)$ at the Fermi surface, and the dimensionless three-particle interaction parameters H_ℓ ($\ell = 0, 1$) are defined by

$$H_\ell = \left(\frac{2p_F M^*}{\pi^2}\rho_0\right) h_\ell\,, \tag{3}$$

where $h_\ell = h_\ell(k_1 = k_2 = k_3 = p_F)$ is given by the angular average

$$\frac{1}{2\ell+1} h_\ell(k_1, k_2, k_3) = \int \frac{\mathrm{d}\Omega_2}{4\pi} \int \frac{\mathrm{d}\Omega_3}{4\pi} \left(\hat{\boldsymbol{k}_1} \cdot \hat{\boldsymbol{k}_2}\right)^\ell h(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)\,. \tag{4}$$

By using empirically and theoretically obtained ranges for the incompressibility,[2)] the effective mass M^*,[4)] and its slope at the Fermi surface,[5,6)] we can deduce the following inequality from (1) and (2):

$$\frac{M}{M^*}(H_0 - H_1) > 1.24 \tag{5}$$

The three-particle amplitudes H_ℓ satisfy a Faddeev equation in the medium, with a 1-particle reducible driving term (first diagram in Fig. 1), and genuine three-particle correlations, which start with the second diagram in Fig. 1. The driving term can be easily estimated by using effective contact interactions of the Landau-Migdal type, and give a contribution between 0.75 and 1.23 to Eq. (5). (Here we used the Landau-Migdal parameters obtained from Skyrme interactions[7)]) and chiral effective field theory.[8)]) This gives us an important hint that two-particle correlations alone cannot satisfy the inequality Eq. (5), and three-particle correlations processes are needed to explain the skewness of nuclear matter.

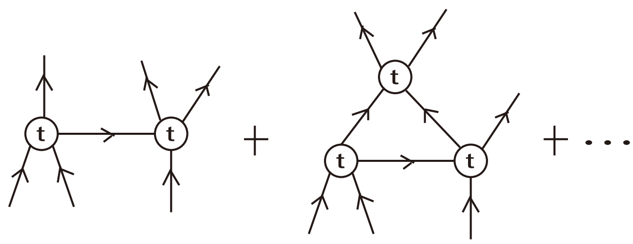

Fig. 1. The first two terms in the Faddeev series of the three-particle amplitudes. Genuine three-particle correlations start with the second diagram. The circles represent two-body t-matrices.

References

1) H. A. Bethe, Phys. Rev. B **138**, 804 (1965).
2) B. -A. Li, B. -J. Cai, L. -W. Chen, J. Xu, Prog. Part. Nucl. Phys. **99**, 29 (2018).
3) J. Negele, H. Orland, *Quantum Many-particle systems* (Springer, 1980).
4) C. Mahaux, P. F. Bortignon, R. A. Broglia, C. H. Dasso, Phys. Rep. **120**, 1 (1985).
5) J. P. Blaizot, B. L. Friman, Nucl. Phys. A **372**, 69 (1981).
6) E. N. E. van Dalen, C. Fuchs, A. Faessler, Phys. Rev. C **72**, 065803 (2005).
7) Z. Zhang, L. -W. Chen, Phys. Rev. C **94**, 064326 (2016).
8) J. W. Holt, N. Kaiser, T. R. Whitehead, Phys. Rev. C **97**, 054325 (2018).

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