PHYSICAL REVIEW C **67**, 037301 (2003)

Landau parameters of nuclear matter in the spin and spin-isospin channels

W. Zuo,[1] Caiwan Shen,[2,3,4] and U. Lombardo[2,5]
[1]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China*
[2]*INFN-LNS, Via S. Sofia 44, I-95123 Catania, Italy*
[3]*China Institute of Atomic Energy, P.O. Box 275(18), Beijing 102413, China*
[4]*Center of Theoretical Nuclear Physics, National Laboratory of Lanzhou Heavy Ion Accelerator, Lanzhou, China*
[5]*Dipartimento di Fisica, Via S. Sofia 64, I-95123 Catania, Italy*
(Received 20 December 2002; published 12 March 2003)

The equation of state of spin and isospin polarized nuclear matter is determined in the framework of the Brueckner theory including three-body forces. The Landau parameters in the spin and spin-isospin sectors are derived as a function of the baryonic density. The results are compared with the Gamow-Teller collective modes. The relevance of G_0 and G_0' for neutron stars is shortly discussed, including the magnetic susceptibility and the neutron star cooling.

DOI: 10.1103/PhysRevC.67.037301 PACS number(s): 21.65.+f, 24.30.Cz, 26.60.+c

The equation of state (EOS) of nuclear matter is a major issue of the quantum-mechanical many-body problem. The reliability of any theoretical prediction has been measured on its capability of reproducing the empirical saturation energy and density, once the convergence of the theory has been firmly established. This is the case of the Brueckner-Bethe-Goldstone theory: the hole-line expansion has been proved in fact to be rapidly converging [1], and the Brueckner-Hartree-Fock (BHF) approximation implemented by three-body forces (3BF) can account for the empirical saturation point [2]. Besides saturation density and energy, additional constraints have been the compressibility extracted from the monopole energy and the symmetry energy from the binding energy of $N \neq Z$ nuclei. In the spin-isospin channel, a further constraint has been provided by the Gamow-Teller (GT) giant resonances (see Ref. [3] for a review). Recently the Landau parameter G_0' has been extracted from the experimental data with very small uncertainty [4]. So it represents a very robust constraint for the EOS of nuclear matter. The theoretical prediction of G_0' demands for extending the calculation of the EOS of nuclear matter to spin-polarized neutrons and protons. Such calculations have been stimulated by the search of a spontaneous transition to a ferromagnetic state to explain the strong magnetic fields observed in neutron stars [5–7], but it can have important implication in the physics of atomic nuclei.

We extended the calculation of the EOS to polarized nuclear matter in the framework of the BHF approximation with the continuous choice for the auxiliary potential. As 2BF we took the Argonne AV_{18} [8] and as 3BF the one from Ref. [9]. Starting from unpolarized nuclear matter at a given density ρ (we only consider symmetric nuclear matter), we ran different polarization states of neutrons and protons

$$\delta_n = \frac{N_\uparrow - N_\downarrow}{N}, \quad \delta_p = \frac{Z_\uparrow - Z_\downarrow}{Z}, \quad \rho = \frac{N+Z}{V}. \tag{1}$$

The results are reported in Fig. 1 for two typical densities of nuclear matter with 2BF (left side) and 2BF plus 3BF (right side). Since the EOS of isospin-polarized nuclear matter fulfills a quadratic law as a function of isospin-symmetry parameter [11,10], and the same is true for the EOS of spin-polarized nuclear matter versus the spin-symmetry parameter [6,7], we fit the EOS (data plotted as symbols in Fig. 1) by the least-square method in the mixed case according to a quadratic law

$$E_A(\rho,\delta_n,\delta_p) - E_A(\rho,0,0) = \sum_{\tau\tau'} \Lambda_{\tau,\tau'}(\rho)\,\delta_\tau \delta_{\tau'}, \tag{2}$$

where $\tau = n,p$ is the isospin quantum number. In symmetric nuclear matter (SNM), the coefficients $\Lambda_{\tau\tau'}$ are related to the zero-order Landau parameters

$$G_0 = G_{nn}^0 + G_{np}^0 = \frac{4N(0)}{\rho}(\Lambda_{nn} + \Lambda_{np}) - 1, \tag{3}$$

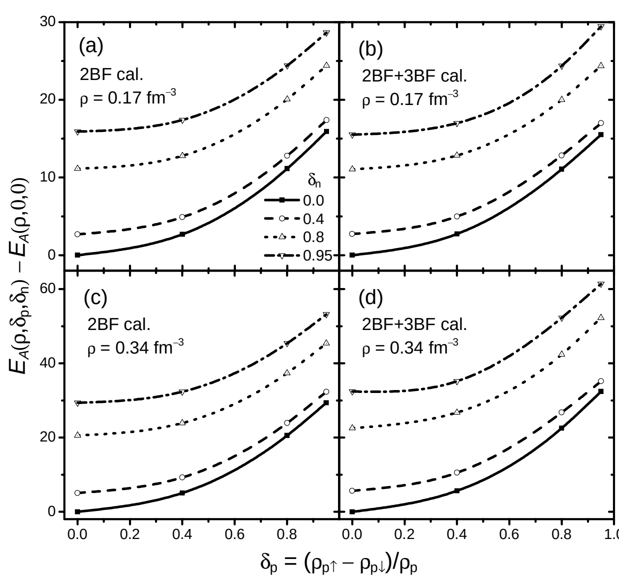

FIG. 1. EOS of spin-polarized nuclear matter. The symbols are from microscopic calculations, and the lines are drawn only to guide the eye.

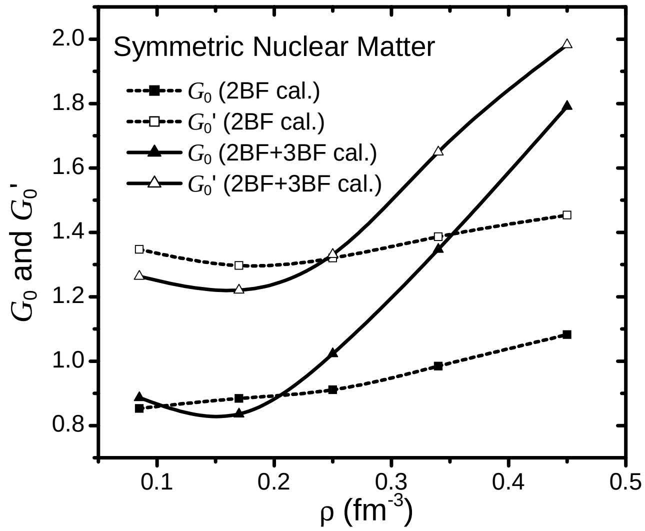

FIG. 2. Landau parameters of SNM in the spin and spin-isospin channel. The square (triangle) symbols are from 2BF (2BF and 3BF) calculations and the solid (open) ones are for G_0 (G_0').

$$G_0' = G_{nn}^0 - G_{np}^0 = \frac{4N(0)}{\rho}(\Lambda_{nn} - \Lambda_{np}) - 1, \qquad (4)$$

where $N(0)$ is the level density at the Fermi surface. In Fig. 2, the two Landau parameters are plotted as a function of the density based on Eqs. (3) and (4).

The Landau parameter G_0' is the strength of the spin-isospin component $V_{\sigma\tau} = G_0'(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$ of the residual interaction [12], which governs the GT giant resonance in nuclei [3]. Its value at the saturation point has been determined with high precision from the experimental excitation energy of the GT resonance on ^{90}Ni [4]. The value reported is $1.182 < G_0' < 1.188$ (we have multiplied by a factor of two according to the definition we adopted). More recent fits on ^{112}Sn and ^{208}Pb within a random phase approximation calculation with Skyrme forces confirm such a prediction [13]. Our nuclear-matter prediction of G_0' at the saturation density, which is about 1.22 including 3BF is in a pretty good agreement with the previous values. The value without 3BF of about 1.30 is in less agreement. Since the behavior of G_0' around the saturation point is very flat, there is no room for large uncertainties in the comparison. Such an agreement provides a further support to the important role played by the microscopic 3BF as to reproduce all saturation properties of nuclear matter. Other predictions of G_0' including 3BF are from phenomenological Skyrme forces, which unfortunately are scattered in wide range of values lower than the experimental one [13].

So far experimental information on G_0 is not enough since spin resonances have only been observed with too small strength compared to other collective modes [3].

The prediction of G_0 and G_0' for densities other than the nuclear density, which is reported in Fig. 2, is of great interest in the study of neutron stars. In connection with the strong magnetic fields observed in neutron stars, some authors [5–7,14] studied the magnetic susceptibility χ in neutron matter and found that χ for degenerate neutron gas gets quenched by the introduction of G_0. This reduction is amplified at high density when including 3BF either in Brueckner calculations [6] and in Monte Carlo many-body simulations [14].

Spin and spin-isospin excitations of nuclear matter are coupled to the weak interaction governing the neutrino emission of URCA processes as well as the neutrino transport in neutron stars. The high-density increase of G_0 and G_0', driven by the 3BF, is expected to have important implications for the neutron star cooling for the sizable enhancement induced by the nuclear correlations on the neutrino mean free path [15].

In conclusion, in this note we reported on BHF calculation of the Landau parameters G_0 and G_0' as a function of baryonic density. The main scope was to point out the large effect of 3BF, especially at high densities. At the 2BF level, there is a wide disagreement with previous Brueckner calculations (see Ref. [16], and references cited therein) that has not yet clearly explained, since one can hardly control and compare the different approximations. On the other hand, our prediction for G_0' has been found to be in very good agreement with the experimental value extracted from GT resonance when 3BF is included. The relevance of the spin Landau parameter for neutron stars has also been discussed in connection with magnetic susceptibility and neutrino mean free path.

This work was supported in part by the Chinese Academy of Science within the ''One Hundred Person Project'' and the NNSF of China under Contract Nos. 10075078, 19935030, and 10047001.

[1] H.Q. Song, M. Baldo, G. Giansiracusa, and U. Lombardo, Phys. Rev. Lett. **81**, 1584 (1998).
[2] W. Zuo, A. Lejeune, U. Lombardo, and J.-F. Mathiot, Nucl. Phys. **A706**, 418 (2002).
[3] F. Osterfeld, Rev. Mod. Phys. **64**, 491 (1992).
[4] T. Suzuki and H. Sakai, Phys. Lett. B **455**, 25 (1999).
[5] I. Vidaña, A. Polls, and A. Ramos, Phys. Rev. C **65**, 035804 (2002).
[6] W. Zuo, U. Lombardo, and C.W. Shen, in *Quark-Gluon Plasma and Heavy Ion Collisions*, edited by W.M. Alberico *et al.* (World Scientific, Singapore, 2002), p. 192.
[7] I. Vidaña and I. Bombaci, Phys. Rev. C **66**, 045801 (2002).
[8] R.B. Wiringa, V.G.J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).
[9] P. Grange, A. Lejeune, M. Martzolff, and J.-F. Mathiot, Phys. Rev. C **40**, 1040 (1989).
[10] W. Zuo, A. Lejeune, U. Lombardo, and J.-F. Mathiot, Eur. Phys. J. A **14**, 469 (2002).
[11] I. Bombaci and U. Lombardo, Phys. Rev. C **44**, 1892 (1991).
[12] A.B. Migdal, *Theory of finite Fermi Systems and Applications*

to Atomic Nuclei (Interscience, New York, 1967).
[13] M. Bender, J. Dobaczewski, J. Engel, and W. Nazarewicz, Phys. Rev. C **65**, 054322 (2002).
[14] S. Fantoni, A. Sarsa, and K.E. Schmidt, Phys. Rev. Lett. **87**, 181101 (2001).
[15] U. Lombardo, C.W. Shen, N. Van Giai, and W. Zuo, in *Proceedings of the International Symposium on Physics of Unstable Nuclei* (Halong Bay, Vietnam, 2002) [Nucl. Phys. (to be published)].
[16] M. Baldo and L.S. Ferreira, Phys. Rev. C **50**, 1887 (1994).