PROPERTIES OF NUCLEAR AND NEUTRON MATTER USING D1 GOGNY FORCE

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In the present work, we investigate the equation of state of hot and cold nuclear and neutron matter using the Gogny effective interaction. The binding energy per particle, symmetry energies, free energy, and pressure are calculated as a function of the density ρ, fm^{-3}, for the nuclear and neutron matter. The results are comparable with previous theoretical estimates using the Seyler—Blanchard effective interaction and the famous calculation of Friedman and Pandharipande using a realistic interaction.

Introduction

The equation of state gives the pressure as a function of temperature and density of a physical system, and is related to both fundamental physics and the applications in gases, condensed matter, astrophysics, and elementary particle theory. It describes also states of matter in extreme density and temperature domains.

In nuclear physics, the equation of state is used to study the properties of nuclear and neutron matter. The nuclear matter is an infinite uniform system of neutrons and protons interacting via a strong nucleon-nucleon force. Such static properties of nuclear matter, like binding energy, asymmetry energies, incompressibility, etc., can be determined with success at zero temperature. Furthermore, at finite temperature, the thermal properties of nuclear matter can be investigated: e.g., free energy, entropy, effective mass, chemical potential, and all possible phases in which the matter may exist. Intermediate-energy heavy-ion collisions and high-energy proton-induced reactions indicated the possibility of the occurrence of a liquid — gas phase transition in nuclear matter, which attracted the interest to study such a system at finite temperature.

In neutron matter, the equation of state is also a very useful tool for studying the properties of neutron stars and their evolution. Different theories and models are used to study the nuclear and neutron matter, such as: Hartree—Fock [1—3], Brueckner theory [4—6], relativistic mean field theory [7—9], variational methods [10—13], and the Thomas—Fermi model [14—17]. In those models, different types of potentials are used, e.g., the Skyrme interaction [18, 19], Reid potential [20], two- and three- (n-n) potentials [13], Paris potential [21], and Seyler – Blanchard (SB) potential [14, 15].

Most of the calculations on nuclear matter consider the symmetric case, i.e., cases where the number of neutrons and protons are equal ($N = Z$). Finite nuclei or neutron stars, which are a closer approximation to nuclear matter, are, in general, asymmetric with $N > Z$. Thermostatic properties of hot asymmetric nuclear matter have also been considered by several authors, e.g., see [22] and [23]. The extension to the case of polarized nuclear matter with $N\uparrow \neq N\downarrow \neq Z\uparrow \neq Z\downarrow$ has been considered by several authors [24—28], where the symmetry energies may be compared with the experimental data.

In the present work, we used a density-dependent interaction which was derived by Gogny [29] to calculate the properties of polarized nuclear and neutron matter.

This interaction has been used only for symmetric [29] and asymmetric nuclear matter [30]. This force has several advantages, it is rather simple to give closed-form analytical expressions for nuclear and neutron matter, has a finite range, and gives a good description of the behavior of pairing phenomena in finite nuclei [31]. It also gives pairing gaps in nuclear matter which are compatible with more sophisticated forces with similar results of the pairing in neutron matter [32—34]. The aim of the present work is to use the Gogny interaction to calculate different properties of polarized nuclear and neutron matter in the general case which has not been considered in previous works. The calculation are then compared with

a) the results obtained using the SB effective interaction,

b) the famous estimates of Friedman and Pandharipande (FP) [13] who used a realistic potential in their calculation for both nuclear and neutron matter.

In the next section, we describe the potential used in the present work along with the different quantities, which give the properties of the nuclear, and neutron matter at zero and finite temperatures. The last section is devoted to a discussion of the results obtained.

1. Theory

1.1. Density-dependent Effective Gogny Interaction

The derivation of the Gogny effective interaction was done essentially along the lines described in [35]. Decharge and Gogny [29] postulated an interaction of the form

$$V(\vec{r}) = \sum_{i=1,2} (W_i + B_i P_\sigma + H_i P_\tau + M_i P_\sigma P_\tau) e^{-\alpha_i r^2} +$$

$$+ t_0 (1 + x_0 P_\sigma) \rho^\beta \delta(\vec{r}_1 - \vec{r}_2). \tag{1}$$

It consists of two central potentials. One is independent of the density [36], and the other part is a density-dependent term with zero range. Here, we used the set of parameters D1 to calculate the different properties of nuclear and neutron matter. The parameters $(t_0, x_0, \alpha_i, \beta, W_i, B_i, H_i, M_i)$, $i = 1,2$, are given in Table 1.

1.2. Nuclear Matter at Zero Temperature

Nuclear matter is an infinite system of nucleons with a fixed ratio of neutron to proton numbers. We mainly consider nuclear matter composed of $N\uparrow$ neutrons with spin up, $N\downarrow$ neutrons with spin down, $Z\uparrow$ protons with spin up, and $Z\downarrow$protons with spin down and with densities $\rho_{n\uparrow}, \rho_{n\downarrow}, \rho_{p\uparrow}$, and $\rho_{p\downarrow}$, respectively. The composition of the system considered may be characterized by the total number of nucleons

$$A = N\uparrow + N\downarrow + Z\uparrow + Z\downarrow\,. \tag{2}$$

Hereby, we refer the reader to one of our previous works [27, 28] for details and notations. The total energy of nuclear matter for the considered system at zero temperature is given by a sum of a kinetic energy part and potential energy part:

$$E = \langle T\rangle + \langle \mathrm{P.E.}\rangle =$$

$$= \langle \frac{\hbar^2 k^2}{2m} \rangle + \frac{1}{2} \sum \langle k_1 k_2 | V_{12} | k_1 k_2 - k_2 k_1 \rangle, \tag{3}$$

where V_{12} is the nucleon-nucleon Gogny interaction, and the energy finally takes the form

$$E/A = E_{\mathrm{vol}} + \frac{1}{2} E_\tau \alpha_\tau^2 + \frac{1}{2} E_\sigma \alpha_\sigma^2 + \frac{1}{2} E_{\sigma\tau} \alpha_{\sigma\tau}^2, \tag{4}$$

where terms higher than those quadratic in α are ignored. E_{vol} is the volume energy per nucleon with $\alpha_x = 0\ (x = \tau, \sigma, \sigma\tau)$, E_τ is the isospin symmetry energy, E_σ is the spin symmetry energy, and $E_{\sigma\tau}$ is the spin-isospin symmetry energy, and

$$\alpha_\tau = (N\uparrow + N\downarrow - Z\uparrow - Z\downarrow)/A, \tag{5a}$$

$$\alpha_\sigma = (N\uparrow + Z\uparrow - N\downarrow - Z\downarrow)/A, \tag{5b}$$

$$\alpha_{\sigma\tau} = (N\uparrow + Z\downarrow - N\downarrow - Z\uparrow)/A. \tag{5c}$$

We finally obtain the following analytical expressions for different energies:

$$E_{\mathrm{vol}} = \frac{3\hbar^2}{10m} \left(\frac{3\pi^2}{2}\right)^{2/3} \rho^{2/3} +$$

$$+ \sum_{i=1,2} \frac{\pi^2}{8\sqrt{\pi\alpha_i^3}} \rho\, (4W_i + 2B_i + 2H_i + M_i) + \frac{3}{8} t_0 \rho^{\beta+1} -$$

$$- \left(\frac{3}{\pi}\right) \left(\frac{3\pi^2}{2}\right)^{1/3} \rho^{1/3} \sum_{i=1,2} (W_i + 2B_i + 2H_i +$$

$$+ 4M_i) \int_0^\infty e^{-\alpha_i r^2} J_1^2(k_{\mathrm{F}} r) dr, \tag{5d}$$

$$E_\tau = \frac{\hbar^2}{3m} \left(\frac{3\pi^2}{2}\right)^{2/3} \rho^{2/3} +$$

$$+ \sum_{i=1,2} \frac{\pi^2}{2\sqrt{\pi\alpha_i^3}} \rho\, (2H_i + M_i) - \frac{1}{4} t_0 (1 + 2x_0) \rho^{\beta+1} -$$

T a b l e 1. Values of the parameters for D1 Gogny force [29]

α, fm^{-2}	W, MeV	B, MeV	H, MeV	M, MeV	β	t_0, MeV $\cdot$fm^4	x_0
2.0408	–402.4	–100	496.2	23.56	1/3	1350	1
0.6944	–21.3	–11.77	–37.27	68.81			

$$-\pi\rho\sum_{i=1,2}(W_i+2B_i+H_i+2M_i)\times$$

$$\times\int_0^\infty r^2e^{-\alpha_i r^2}(J_0^2(k_\mathrm{F}r)-J_1^2(k_\mathrm{F}r))dr+$$

$$+\pi\rho\sum_{i=1,2}(H_i+2M_i)\int_0^\infty r^2e^{-\alpha_i r^2}(J_0^2(k_\mathrm{F}r)+J_1^2(k_\mathrm{F}r))dr, \tag{5e}$$

$$E_\sigma=\frac{\hbar^2}{3m}\left(\frac{3\pi^2}{2}\right)^{2/3}\rho^{2/3}+$$

$$+\sum_{i=1,2}\frac{\pi^2}{2\sqrt{\pi\alpha_i^3}}\rho\,(2B_i+M_i)-\frac{1}{4}t_0(1-2x_0)\rho^{\beta+1}-$$

$$-\pi\rho\sum_{i=1,2}(W_i+B_i+2H_i+2M_i)\times$$

$$\times\int_0^\infty r^2e^{-\alpha_i r^2}(J_0^2(k_\mathrm{F}r)-J_1^2(k_\mathrm{F}r))dr+$$

$$+\pi\rho\sum_{i=1,2}(B_i+2M_i)\int_0^\infty r^2e^{-\alpha_i r^2}(J_0^2(k_\mathrm{F}r)+J_1^2(k_\mathrm{F}r))dr, \tag{5f}$$

$$E_{\sigma\tau}=\frac{\hbar^2}{3m}\left(\frac{3\pi^2}{2}\right)^{2/3}\rho^{2/3}+\sum_{i=1,2}\frac{\pi^2}{2\sqrt{\pi\alpha_i^3}}\rho-\frac{1}{4}t_0\rho^{\beta+1}-$$

$$-\pi\rho\sum_{i=1,2}(W_i+2B_i+H_i+2M_i)\times$$

$$\times\int_0^\infty r^2e^{-\alpha_i r^2}(J_0^2(k_\mathrm{F}r)-J_1^2(k_\mathrm{F}r))dr+$$

$$+\pi\rho\sum_{i=1,2}(B_i+H_i+2M_i)\times$$

$$\times\int_0^\infty r^2e^{-\alpha_i r^2}(J_0^2(k_\mathrm{F}r)+J_1^2(k_\mathrm{F}r))dr. \tag{5g}$$

The pressure of nuclear matter is defined as

$$P=\rho^2\partial E/\partial\rho, \tag{6}$$

where ρ is the density of symmetric nuclear matter.

1.3. Nuclear Matter at Finite Temperature

It is well known from classical thermodynamics [37] that the thermodynamic properties of nuclear matter are determined completely if the free energy F is known in terms of the density ρ and temperature T,

$$F=E-TS, \tag{7}$$

E being the total energy and S is the entropy. Using the T^2-approximation [28], we obtain the entropy S, free energy F, and pressure P as follows:

$$S_T=\frac{T}{6}\left(\frac{2m^*}{\hbar^2}\right)\left(\frac{3\pi^2}{2}\right)^{1/3}\rho^{-2/3}, \tag{8}$$

$$F_T=E_\mathrm{vol}-\frac{T^2}{6}\left(\frac{2m^*}{\hbar^2}\right)\left(\frac{3\pi^2}{2}\right)^{1/3}\rho^{-2/3}, \tag{9}$$

$$P_T=P(T=0)+\frac{T^2}{9}\left(\frac{2m^*}{\hbar^2}\right)\left(\frac{3\pi^2}{2}\right)^{1/3}\rho^{1/3}, \tag{10}$$

$$\left(\frac{\hbar^2}{2m^*}\right)=\frac{\hbar^2}{2m}+\frac{1}{3\pi}\left(\frac{3\pi^2}{2}\right)^{2/3}\rho^{2/3}\sum_{i=1,2}(W_i+$$

$$+2B_i+2H_i+4M_i)\int_0^\infty r^3e^{-\alpha_i r^2}J_1(k_\mathrm{F}r)dr, \tag{11}$$

where m^* is the effective mass, k_F is the Fermi momentum, and $J_1(k_\mathrm{F}r)$ is the spherical Bessel function.

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1.4. Neutron Matter

Assume that we have N neutrons in the periodicity box of volume Ω. Among the N neutrons there are $N\uparrow$ neutrons with spin up and $N\downarrow$ neutrons with spin down ($N = N\uparrow + N\downarrow$). For a fixed density $\rho = N/\Omega$, the ground state energy $E(N\uparrow, N\downarrow)$ depends on the spin excess parameter

$$\alpha_\sigma = (N\uparrow - N\downarrow)/N, \tag{12}$$

and the binding energy per neutron in this case is written as

$$E/A = E_{\text{vol}} + \frac{1}{2}E_\sigma \alpha_\sigma^2, \tag{13a}$$

where terms higher than quadratic in α_σ are neglected and

$$E_{\text{vol}} = \frac{3\hbar^2}{10m}\left(3\pi^2\right)^{2/3}\rho^{2/3} +$$

$$+\sum_{i=1,2}\frac{\pi^2\rho}{8\sqrt{\pi\alpha_i^3}}\left(2W_i + B_i + 2H_i + M_i\right) +$$

$$+\frac{1}{4}t_0(1-x_0)\rho^{\beta+1} - \left(\frac{3}{\pi}\right)\left(3\pi^2\right)^{1/3}\rho^{1/3}\times$$

$$\times\sum_{i=1,2}(W_i + 2B_i + H_i + 2M_i)\int\limits_0^\infty e^{-\alpha_i r^2}J_1^2(k_{\text{F}}r)dr, \tag{13b}$$

$$E_\sigma = \frac{\hbar^2}{3m}\left(3\pi^2\right)^{2/3}\rho^{2/3} + \sum_{i=1,2}\frac{\pi^2\rho}{2\sqrt{\pi\alpha_i^3}}(B_i + M_i) -$$

$$-\frac{1}{2}t_0(1-x_0)\rho^{\beta+1} - 2\pi\rho\sum_{i=1,2}(W_i + B_i + H_i + M_i)\times$$

$$\times\int\limits_0^\infty r^2 e^{-\alpha_i r^2}(J_0^2(k_{\text{F}}r) - J_1^2(k_{\text{F}}r))dr +$$

$$+2\pi\rho\sum_{i=1,2}(B_i + M_i)\int\limits_0^\infty r^2 e^{-\alpha_i r^2}(J_0^2(k_{\text{F}}r) +$$

$$+J_1^2(k_{\text{F}}r))dr. \tag{13c}$$

The pressure is defined as in the previous case of nuclear matter.

The thermodynamic properties of neutron matter are determined completely if the free energy F is known in terms of the temperature T and the density of neutron matter ρ,

$$F = E - TS. \tag{14}$$

Using the T^2-approximation, we obtain the entropy S, free energy F, and pressure P as follows:

$$S_T = \frac{T}{12}\left(\frac{2m_n^*}{\hbar^2}\right)\left(3\pi^2\right)^{1/3}\rho^{-2/3}, \tag{15}$$

$$F_T = E_{\text{vol}} - \frac{T^2}{12}\left(\frac{2m_n^*}{\hbar^2}\right)\left(3\pi^2\right)^{1/3}\rho^{-2/3}, \tag{16}$$

$$P_T = P(T=0) + \frac{T^2}{9}\left(\frac{2m_n^*}{\hbar^2}\right)\left(3\pi^2\right)^{1/3}\rho^{1/3}, \tag{17}$$

$$\left(\frac{\hbar^2}{2m_n^*}\right) = \frac{\hbar^2}{2m_n} + \frac{1}{24\pi}\left(3\pi^2\right)^{2/3}\rho^{2/3}\times$$

$$\times\sum_{i=1,2}(W_i + 2B_i + H_i + 2M_i)\int\limits_0^\infty r^3 e^{-\alpha_i r^2}J_1(k_{\text{F}}r)dr, \tag{18}$$

where m_n^* is the neutron effective mass. The magnetic susceptibility is a measure of the energy required to reproduce a net spin alignment in a given direction. It is inversely proportional to the energy required to polarize the spins. Following Haensel [24], one can write an expression for the ratio of the magnetic susceptibility of neutron matter to that of the Fermi gas of noninteracting neutrons as

$$\chi_{\text{F}}/\chi = \frac{3}{2}(E_\sigma/\varepsilon_{\text{F}}), \tag{19}$$

where ε_{F} is the Fermi energy for unpolarized neutron matter:

$$\varepsilon_{\text{F}} = \hbar^2 k_{\text{F}}^2/2m_n. \tag{20}$$

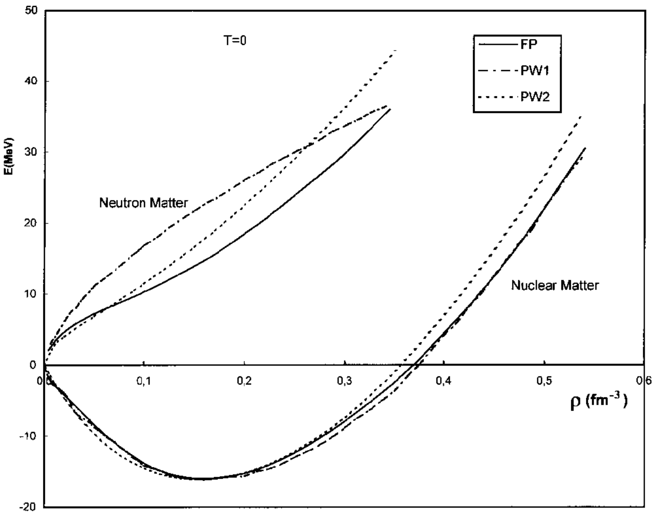

Fig. 1. Free energy (MeV) against the density ρ (fm^{-3}) for the three potentials (Gogny D1 [PW], SB [27, 40], and FP [13] at $T = 0$ for nuclear and neutron matter

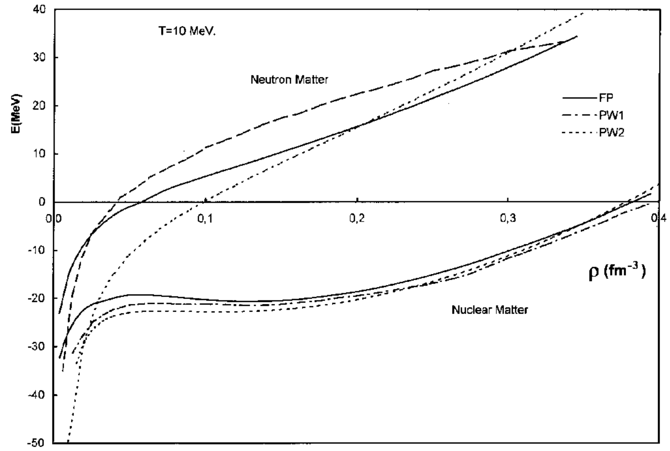

Fig. 2. Same as in Fig. 1 but for $T = 10$ MeV

1.5. Results and Discussion

In the present work, we used the D1 Gogny force to calculate some physical properties of the nuclear and neutron matter, where some of them for polarized nuclear matter, are presented for the first time. It is composed of two Gaussians, one of which simulates a short-range force and the other one an intermediate range. Also, it contains all possible admixtures of spin, isospin, and space exchange operators p_σ, p_τ and p_x. The other part is a density-dependent zero range, which together with the Gaussian shapes give rather simple analytical expressions which reduce the computation time.

T a b l e 2. The nuclear matter properties calculated with the D1 Gogny force

k_F, fm^{-1}	E/A, MeV	E_τ, MeV	E_σ, MeV	$E_{\sigma\tau}$, MeV	m^*/m
1.348	–16.12	61.54	55.14	62.37	0.72

T a b l e 3. Symmetry energies of nuclear matter in MeV

	Present Work	A	B	C	D
E_τ	61.54	52	46	44	52
E_σ	55.14	63	57	53	67
$E_{\sigma\tau}$	62.37	62	57	48	43

N o t e. Brueckner theory with the Reid soft core potential [24] (A); from the Landau parameters of [38] (B), from the Landau parameters of [39] (C), from the Landau parameters of [40] (D). The present work calculated at $k_F = 1.3489$ fm^{-1}. Calculated at $k_F = 1.36$ fm^{-1}.

The parameters were chosen to fit the bulk properties of nuclei and some collective states as well as the nuclear matter properties. Furthermore, some of its parameters may be varied without affecting too much most of the properties which were fitted originally. The results obtained are compared with another effective interaction using a generalized SB potential [28], which is extended to study polarizable nuclear or neutron matter. The comparison is also made with the realistic force calculation [13]. The parameters $(t_0, x_0, \alpha_i, \beta, W_i, B_i, H_i, M_i)$, $i = 1, 2$, are shown in Table 1. At $k_F = 1.348$ fm^{-1}, we present the values of the volume energy E_{vol} and the symmetry energies for polarized nuclear matter E_τ, E_σ and $E_{\sigma\tau}$ in Table 2. The results are comparable with previous theoretical estimates as shown in Table 3. From Table 3, one observes that E_τ is slightly greater than that obtained by previous calculations [24, 38—40], whereas E_σ is comparable with that in [38, 39]. $E_{\sigma\tau}$ is in good agreement with that of [31]. The free energy at temperatures $T = 0$ and 10 MeV are presented in Figs. 1 and 2 for both nuclear and neutron matter using the Gogny D1 force (present work (PW)) and our previous calculation using a modified Seyler—Blanchard effective interaction MSB [27, 40] along with the results of FP [13] using realistic forces. The potentials agree very well in the case of nuclear matter where the results of the present calculation are closer to those of FP. For the neutron matter, the three results are comparable and have almost the same shape. The pressure density curves for both nuclear and neutron matter are given in Figs. 3 and 4 for the temperatures $T = 0$ and 10 MeV, respectively. Here again, we have a good agreement with

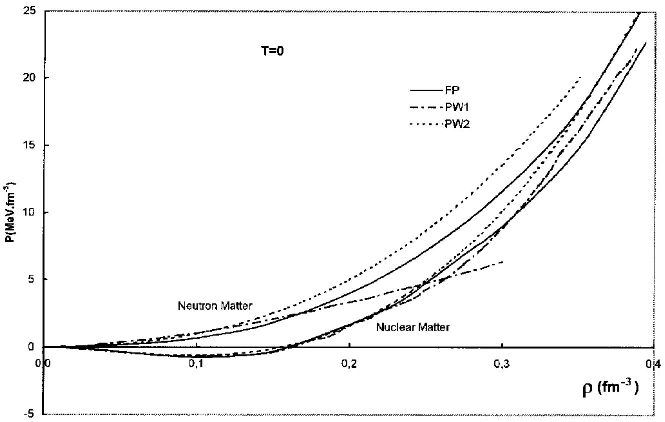

Fig. 3. Pressure vs density for three potentials (Gogny D1 [PW], SB [27, 40] and FP [13] at $T = 0$ for nuclear and neutron matter

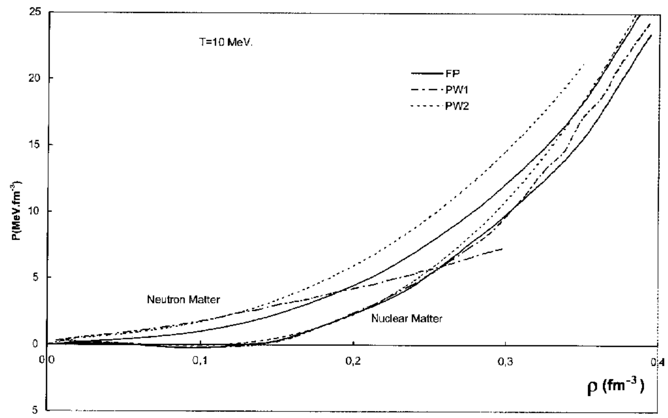

Fig. 4. Same as in Fig. 3 but for $T = 10$ MeV

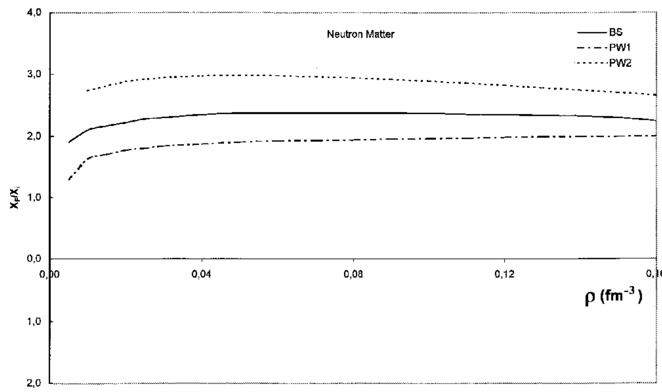

Fig. 5. Comparison of the quantity χ_F/χ as a function of the Fermi momentum k_F (fm^{-1}) using the Gogny D1 [PW] and SB [27, 40] potentials with the results obtained in [41]

the FP values in the nuclear matter case where, as for the neutron matter case, the agreement is fair.

Our results of the ratio of the magnetic susceptibilities χ_F/χ are plotted in Fig. 5 for the neutron matter case, using the SB potential and the Gogny D1 force as a function of Fermi momentum k_F together with the results obtained [41]. The results have the same behavior, i.e. it increases with the density until it reaches a maximum and then decreases.

Since the analysis of the neutron star with zero proton content is very unrealistic, we present the energy E and pressure P at zero temperature for pure neutron matter with zero proton content and neutron matter with the 5% proton ratio in Table 4. From Table 4, one concludes that the system is still unbound, and the behavior of E and P as a function of ρ is the same with little differences between the two sets of calculations.

T a b l e 4. Comparison between the energy E and pressure P at zero temperature between pure neutron matter and neutron matter with 5% proton ratio

ρ, fm^{-3}	E, MeV Pure neutron matter	E, MeV 5% proton ratio	P, MeV·fm^{-3} Pure neutron matter	P, MeV·fm^{-3} 5% proton ratio
0.250	7.20	6.59	0.01	0.005
0.563	11.80	10.74	0.35	0.313
0.750	13.90	12.64	0.65	0.587
0.100	16.85	15.30	1.03	0.947
0.125	19.37	17.63	1.50	1.394
0.163	22.91	20.96	2.35	2.232
0.200	26.10	24.02	3.30	3.215
0.225	28.13	25.99	4.00	3.940
0.250	30.00	27.85	4.70	4.675
0.275	31.77	29.62	5.49	5.518
0.300	33.75	31.62	6.30	6.428

In summary, our results show that the D1 force [PW] gives reasonable values for the properties of nuclear matter in comparison with the realistic force calculations, which are in turn related to the phase shifts. Similar results are obtained using the SB potential, where we present the nuclear matter calculation [28] and the neutron matter case [40]. For the neutron matter, the agreement is fair between the three potentials considered in this work. In [27] and [40], the parameters of the SB interaction potential are changed to fit the polarized nuclear matter. Also we considered the same SB potential which is modified by adding terms to it which depend on the different proton and neutron densities in the polarized case [28]. The results of our calculation are made for the Gogny force using simple analytical expressions without modifying the potential functional form or its parameters, and it looks very promising in describing a large number of nuclear properties despite its simple form. In conclusion, the Gogny interaction may be better used because it can overcome the disadvantages of the famous Skyrme interaction [18] (which has a zero-range and density-dependent part) as well as those of the Brink and Boeker interaction [40] (which has a finite-range force), being a density-dependent and finite-range interaction.

1. *Kermann A.K., Svenne J.P., Villars F.M.H.*// Phys. Rev. **147**, 710 (1960).
2. *Bassichis W.H., Kermann A.K., Svenne J.P.*// Ibid. **160**, 746 (1967).
3. *Vautherin D., Brink D.M.*//Ibid. C**5**, 626 (1972).
4. *Brueckner K.A., Gammel J.L.*//Ibid. **105**, 1679 (1957).
5. *Brueckner K.A., Gammel J.L.*// Ibid. **109**, 1023 (1958).
6. *Brueckner K.A., Gammel J.L., Weitzner H.*// Ibid. **110**, 431 (1959).
7. *Walecka J.D.*// Ann.Phys. **83**, 491 (1974).
8. *Serot B.D.*// Phys. Lett. B**86**, 146 (1979).
9. *Serot B.D., Walecka J.D.*// Adv. Nucl. Phys. **16**, 1 (1986).
10. *Pandharipande V. R.*// Nucl. Phys. A**174**, 641 (1971).
11. *Pandharipande V.R.*// Ibid. **178**, 123 (1971).
12. *Schmidt K.E., Pandharipande V.R.*// Phys. Lett. B**87**, 11 (1979).
13. *B. Friedman and V. R. Pandharipande*// Nucl. Phys. A**361**, 502 (1981).
14. *Seyler R.G., Blanchard C.H.*// Phys. Rev. **124**, 227 (1961).
15. *Seyler R.G., Blanchard C.H.*// Ibid. **131**, 355 (1963).
16. *Myers W.D., Swiatecki W.J.*// Ann. Phys. **55**, 395 (1969).
17. *Kupper W.A., Wegmann G., Hilf E.*//Ibid. (N.Y.) **88**, 454 (1974).
18. *Skyrme T.H.R.*// Phil. Mag. **1**, 1043 (1956); Nucl. Phys. **9**, 615 (1959).
19. *Reid R.V.*// Ann. Phys. **50**, 411 (1968).
20. *Pandharipande V.R., Bethe H.A.*// Phys. Rev. C**7**, 1312 (1973).
21. *Lacombe M., Loisean B., Richard J.M.*//Ibid. **21**, 861 (1980).
22. *Hassan M.Y.H., Montasser S.S.*// Acta phys. pol. B**11**, 567 (1980).
23. *Barranco M., Buchler J.R.*// Phys. Rev. C**22**, 1729 (1980).
24. *Dabrowski J., Haensel P.*//Ibid. **7**, 916 (1973).
25. *Dabrowski J.*// Acta phys. pol. B**7**, 657 (1976).
26. *Hassan M.Y.H., Montasser S.S., Ramadan S.*// J. Phys. G**6**, 1229 (1980).
27. *Mansour H.M.M., Hammad M., Hassan M.Y.M.* //Phys. Rev. C**56**, 1418 (1997).
28. *Mansour H.M.M., Ramadan Kh.A.*//Ibid. **57**, 1744 (1998).
29. *Decharge J., Gogny D.*//Ibid. **21**, 1568 (1980).
30. *Huang S.W., Fu M.Z., Wu S.S., Yang S.D.*// Mod. Phys. Lett. A**5**, 1071 (1990).
31. *Bengtsson R., Schuck P.*// Phys. Lett. B**89**, 321 (1980).
32. *Kucharck H., Ring P., Schuck P.*// Z. Phys. A**334**, 119 (1989).
33. *Kucharck H., Ring P., Schuck P. et al.*// Phys. Lett. B**216**, 249 (1989).
34. *Lazzari G., De Blasio F., Lazzari C.* //Acta phys. slov. **44**, 29 (1994).
35. *Brink D.M. , Boeker E.*// Nucl. Phys. **91**, 1 (1967).
36. *Volkov A.B.*//Ibid. **74**, 33 (1965).
37. *Landau L.D., Lifshitz L.M.* Statistical Physics.—New York: Pergamon, 1969.
38. *Migdal A.B.* Theory of Finite Fermi Systems and Applications to Atomic Nuclei.— London: Interscience, 1967.
39. *Backman S.O.*// Nucl. Phys. A**120**, 593 (1968).
40. *Hammad M.*: Ph. D. Thesis /Zagazig University.— Egypt.
41. *Behera B., Satpathy R.K.J.*// J. Phys. G**5**, 1085 (1979).

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ВЛАСТИВОСТІ ЯДЕРНОЇ ТА НЕЙТРОННОЇ МАТЕРІЇ З ВИКОРИСТАННЯМ ПОТЕНЦІАЛУ ГОГНІ

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Р е з ю м е

Досліджено рівняння стану гарячої та холодної ядерної та нейтронної матерії з використанням ефективної взаємодії Гогні. Енергію зв'язку на одну частинку, енергію симетрії, вільну енергію і тиск розраховано як функцію густини ρ (у фм$^{-3}$) для ядерної та нейтронної матерії. Ці результати порівняно з попередніми теоретичними оцінками з використанням ефективної взаємодії Сейлера—Бланчарда та з відомим розрахунком Фрідмана і Пандхаріпанде, де використано реальну взаємодію.