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NEUTRON MATTER WITH RECENT NONLOCAL SEPARABLE NUCLEON-NUCLEON POTENTIALS

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The nonlocal separable nucleon-nucleon potentials, recently applied in the nuclear matter calculations, are used within the frame of the Brueckner theory for the calculation of the equation of state of the pure neutron matter. The results for the potentials, which proved to be most promising in the nuclear matter calculations, coincide with those obtained for the Reid soft core potential in the lowest order Brueckner theory.

In the last years considerable successes have been achieved in fitting the two-nucleon data by models of the nucleon-nucleon interaction. These models are based either on the field-theoretical considerations or on phenomenological description. However the two-nucleon data are insufficient to determine uniquely the two-nucleon interaction, e.g., they can be fitted equally well by the local [1] as well as the recent nonlocal separable [2–5] phenomenological nucleon-nucleon interactions. Thus, one needs more information to reduce the ambiguities in the choice of the nucleon-nucleon potentials. The three- and, more generally, many-body calculations involve off-shell matrix elements of the nucleon-nucleon interaction, which cannot be determined from the two-nucleon data. The simplest test of this kind is the nuclear (or neutron) matter calculation.

In this paper we present the results of the calculation of the properties of the infinite neutron matter with the recent nonlocal separable nucleon-nucleon interactions [2–5], applied just recently in the nuclear matter calculations [6]. Such calculations are of a considerable interest in astrophysics because the recently discovered pulsars are believed

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to be neutron stars, and in the normal nuclear density region ($\varrho_0 = 0.17$ nucleon/fm^3) the neutron star matter is expected to consist mainly of neutrons with a small admixture of protons, electrons and muons [7]. A study of the dense, cold neutron matter, especially above the nuclear density, represents a very sensitive test for the assumed form of the nuclear interaction.

We have calculated the energy per particle in the neutron matter in the lowest order Brueckner theory using standard approximations. The contribution to the potential energy from $L > 2$, $J > 2$ partial waves has been estimated in the first Born approximation for OP EP. The calculational procedure applied has been essentially the same as that described in Ref. [8]. We have used the four following parametrizations of the nonlocal separable nucleon-nucleon interactions: the modified Mongan potential (M5) with the $^1S_0$ interaction of Hammann and Ho-Kim [5] and the original parametrization of Mongan [2] in the remaining states; the new potential of Hammann, Desgrolard and Chetouani [4] (HDC); the set I of the Graz potential [3] (G1), and the parametrization of Doleschall [9] in the P states with the Hammann, Desgrolard and Chetouani parametrization in the remaining states (HDCD). The parametrizations M5 and HDC supplemented by the Pieper [10] parametrization of the interaction in the $^3S_1$—$^3D_1$ channel appear to be most promising nonlocal separable interactions in the nuclear matter calculations, where they give for the first time results similar to those obtained with the Reid soft core (RSC [1]) potential [6]. On the other hand they reproduce very well the two-nucleon data. Our results for the energy per neutron in neutron matter, shown in Fig. 1, reflect the specific

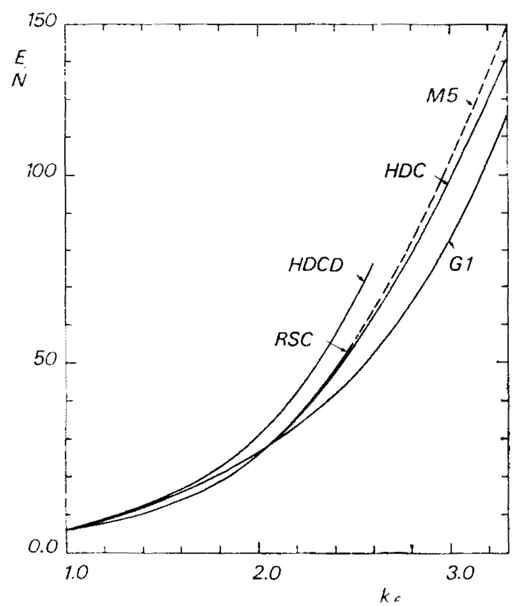

Fig. 1. Energy per neutron in neutron matter (in MeV) versus k_F (in fm^{-1}) for the potentials considered. The lowest order Brueckner theory results of Ref. [11] for the RSC potential are also shown for comparison. The parts of curve M5 for $k_F < 2.5$ fm^{-1} and curve HDC for $k_F < 2.3$ fm^{-1} cannot be graphically distinguished from the RCS curve

properties of the neutron-neutron potentials. Up to the density corresponding to $k_F = 2.5\ \mathrm{fm}^{-1}$, which is 3.2 times greater than the normal nuclear density ϱ_0, our results for the M5 and HDC potentials coincide with the lowest order Brueckner theory results of Siemens and Pandharipande for the RSC potential [11]. On the other hand, the G1 parametrization, which overbinds nuclear matter at the too high equilibrium density, leads to the E/N values which are considerably lower than those obtained for the RSC potential. The parametrization of the nucleon-nucleon interaction in the P states, introduced by Doleschall [9], yields an excellent fit to the two-nucleon data. However, this force leads at the normal nuclear density to the P-waves contribution to the potential energy of nuclear matter, which is 5 — 6 MeV more repulsive than the corresponding RSC contribution [6]. The same effect, however much more pronounced at higher densities, is observed in our neutron matter results. e.g., at $\varrho = 3.2\ \varrho_0$ the HDCD potential yields the total P contribution which is 14 MeV greater than the corresponding RSC contribution. In our opinion this effect is due to the quite unusual form of the off-shell extension of the on-the-energy-shell interaction. Namely, the Doleschall formfactors resemble rather Padé approximants, while in the M5, HDC and G1 parametrizations the generalized Yamaguchi [12] formfactors are used.

The lowest order (standard) Brueckner theory with zero potential energy in the intermediate states gives only the two-body contribution to the potential energy per particle in neutron matter. The higher order contributions from the Goldstone diagrams with

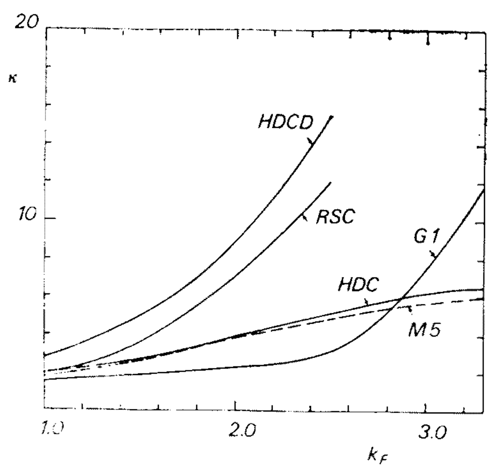

Fig. 2. Values of the defect parameter (in %) versus k_F (in fm^{-1}) for the potentials considered. The lowest order Brueckner theory results of Ref. [11] for the RSC potential are also shown for comparison

three and more hole lines should be calculated explicitly and added to the two-body contribution. The importance of these higher order contributions is determined by the defect parameter κ, which gives a measure of the average probability of a normally occupied neutron state being empty [13]. Calculated values of defect parameter for the potentials considered, plotted in Fig. 2, suggest that the lowest order Brueckner theory with these potentials could be applied to neutron matter at the densities much higher than the normal nuclear density. However, at high densities (corresponding to $k_F \approx 2.7$ fm^{-1} in the case of the HDCD potential and k_F greater than 3.3 fm^{-1} in the case of the remaining potentials) the single-particle potential for the hole state becomes positive near the Fermi surface, leading to the unphysical singularities in the two-neutron propagators. Thus, the choice of the zero single-particle potential in the intermediate states, so successful near nuclear density, leads to the failure of the calculational scheme at high densities.

The quantity of interest for astrophysical calculations is the pressure of neutron matter, P, which is related to the slope of the E/N curves shown in Fig. 1. The pressure of a substance at zero temperature (or entropy) is related to the energy per particle by:

$$P = \varrho^2 \frac{d}{d\varrho}\left(\frac{E}{N}\right),$$

where in the case of neutron matter $\varrho = \dfrac{k_F^3}{3\pi^2}$.

The functional dependence of the pressure on the density (equation of state) can be combined with the equations of gravitation of the general relativity theory so as to get the distribution of density and pressure in a neutron star. Our results for the $P(\varrho)$ are given in Table I. The results for the M5 potential coincide quite well with those obtained

TABLE I

The equations of state for the potentials considered

k_F (fm^{-1})	ϱ (fm^{-3})	P (dynes/cm^2)			
		M5	HDC	G1	HDCD
0.5	4.22×10^{-3}	7.27×10^{30}	6.93×10^{30}	7.38×10^{30}	7.78×10^{30}
1.0	3.38×10^{-2}	1.74×10^{32}	1.60×10^{32}	2.14×10^{32}	2.01×10^{32}
1.3	7.42×10^{-2}	7.24×10^{32}	6.93×10^{32}	8.45×10^{32}	7.98×10^{32}
1.6	1.38×10^{-1}	2.66×10^{33}	2.67×10^{33}	2.56×10^{33}	2.95×10^{33}
1.9	2.32×10^{-1}	8.41×10^{33}	8.52×10^{33}	6.61×10^{33}	9.85×10^{33}
2.2	3.60×10^{-1}	2.25×10^{34}	2.24×10^{34}	1.58×10^{34}	2.81×10^{34}
2.5	5.28×10^{-1}	5.22×10^{34}	5.05×10^{34}	3.70×10^{34}	6.91×10^{34}
2.8	7.41×10^{-1}	1.07×10^{35}	9.95×10^{34}	8.34×10^{34}	
3.1	1.01	2.02×10^{35}	1.81×10^{35}	1.78×10^{35}	
3.3	1.21	2.95×10^{35}	2.55×10^{35}	2.81×10^{35}	

for the HDC potential. On the other hand, the behaviour of $P(\varrho)$ for the G1 and HDCD potentials is quite different. Namely, in the normal nuclear density region the G1 potential yields the much "softer" equation of state, while the neutron matter with the HDCD potential is much "stiffer". The RSC results of Pandharipande [14] are in agreement with our equations of state for the M5 and HDC potentials at the densities $\varrho < 0.5$ neutrons/fm^3. At higher densities, however, the M5 and HDC potentials yield the equation of state which is "softer" than that obtained by Pandharipande [14] for the RSC potential in the lowest order variational calculation.

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