Available online at www.sciencedirect.com
SCIENCE DIRECT®
Physics Letters B 609 (2005) 232–240
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Spin–orbit and tensor interactions in homogeneous matter of nucleons: accuracy of modern many-body theories

I. Bombaci [a], A. Fabrocini [a], A. Polls [b], I. Vidaña [c]

[a] *Dipartimento di Fisica "E. Fermi", Università di Pisa, and INFN, Sezione di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*
[b] *Departament d'Estructura i Constituents de la Matèria, Diagonal 645, Universitat de Barcelona, E-08028 Barcelona, Spain*
[c] *Gesellschaft für Schwerionenforschung (GSI), Planckstrasse 1, D-64291 Darmstadt, Germany*

Received 15 November 2004; accepted 24 January 2005

Available online 2 February 2005

Editor: J.-P. Blaizot

Abstract

We study the energy per particle of symmetric nuclear matter and pure neutron matter using realistic nucleon–nucleon potentials having noncentral tensor and spin–orbit components, up to three times the empirical nuclear matter saturation density, $\rho_0 = 0.16$ fm^{-3}. The calculations are carried out within the frameworks of the Brueckner–Bethe–Goldstone (BBG) and correlated basis functions (CBF) formalisms, in order to ascertain the accuracy of the methods. The two hole-line approximation, with the continuous choice for the single particle auxiliary potential, is adopted for the BBG approach, whereas the variational Fermi hypernetted chain/single operator chain theory, corrected at the second order perturbative expansion level, is used in the CBF one. The energies are then compared with the available quantum and variational Monte Carlo results in neutron matter and with the BBG, up to the three hole-line diagrams. For neutron matter and potentials without spin–orbit components all methods, but perturbative CBF, are in reasonable agreement up to $\rho \sim 3\rho_0$. After the inclusion of the LS interactions, we still find agreement around ρ_0, whereas it is spoiled at larger densities. The spin–orbit potential lowers the energy of neutron matter at ρ_0 by $\sim$ 3–4 MeV per nucleon. In symmetric nuclear matter, the BBG and the variational results are in agreement up to $\sim 1.5\rho_0$. Beyond this density, and in contrast with neutron matter, we find good agreement only for the potential having spin–orbit components.

PACS: 21.65.+f; 21.10.Dr; 21.60.Gx; 24.10.Cn

Keywords: Nuclear matter; Equation of state; Many-body theory

E-mail address: adelchi.fabrocini@df.unipi.it (A. Fabrocini).

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2005.01.067

Homogeneous matter of nucleons plays an important role in modern nuclear physics. For instance, short range correlations in nuclei, induced by the strong nucleon–nucleon (NN) interaction, are expected not to be very different from those in infinite nuclear matter at a corresponding local density. This prediction has found quantitative confirmation in the studies of quantities like inclusive and exclusive electron scattering cross sections. In general, the study of infinite matter of nucleons, starting from a Hamiltonian containing realistic NN interactions, shows dramatic departures from the predictions of the independent particle models (IPM) [1]. A clear example is the depletion of the momentum distribution, $n(k)$, at momenta below the Fermi momentum, $k < k_F$, and the corresponding appearance of a large momentum tail [2–7], otherwise absent in any IPM. An object of intensive study in this field is the equation of state (EOS) of nuclear matter, both for symmetric nuclear matter (SNM) and pure neutron matter (PNM). The aims are (i) testing the validity of microscopic interactions, fitted to the properties of the light ($A = 2$ and 3) nuclei, in a many-body system and (ii) checking the accuracy of the adopted methodologies in a demanding environment. Moreover, an accurate knowledge of the EOS, and in particular of the density dependence of the symmetry energy [8], is needed in order to determine, with the highest possible level of confidency, the structure and the thermal evolution of the neutron stars [9]. In this respect, it is compulsory to use both realistic Hamiltonians as well as reliable many-body techniques.

From the point of view of the NN interaction, large progresses have been achieved in the last decade. Modern potentials [10–12] are "phase shift equivalent", since all fit a huge set of NN scattering data [13] below 350 MeV with χ^2 per datum close to 1. Three-nucleon forces have been also introduced, and the resulting Hamiltonian provides a nice reproduction of the binding and low-lying states energies of light nuclei ($A \leqslant 10$) [14,15].

In parallel to the advances in the knowledge of the nuclear interaction, and partly motivated by its strong state dependence, several many-body theories have been noticeably pushed forward. In this Letter we use, and compare, the correlated basis functions (CBF) [16,17] and the Bethe–Brueckner–Goldstone (BBG) [18] theories.

CBF is particularly suited to deal with strongly interacting systems, since the non-perturbative correlation effects induced by the interaction are directly embedded into the basis states through an appropriate many-body correlation operator acting on some given model wave function. It is clear that complicated interactions are expected to induce similarly non trivial correlations. For instance, (i) the strong one-pion-exchange potential, essential to provide the nuclear binding, reflects into the existence of a long–medium range tensor-like correlation, whereas (ii) the strong, short range (about 0.5 fm) NN repulsion, preventing the nuclear systems from collapsing, generates a mostly central correlation so strong that the wave function is almost vanishing at these low internucleon distances. Operator matrix elements and expectation values between CBF states are, by far, more realistic than those evaluated in a free Fermi gas (FG) basis. As a consequence, a CBF based perturbative expansion is expected to converge much faster. The obvious drawback is that the matrix elements are difficult to be accurately computed. The zeroth order of the CBF perturbative theory corresponds to the purely variational estimates, since the correlated ground state wave functions are fixed by minimizing the energy with respect to the correlation parameters. Within CBF the matrix elements can be computed either by cluster expansions in Mayer-like diagrams and integral equations methods or by Monte Carlo (MC) based evaluations. The Fermi hypernetted chain/single operator chain (FHNC/SOC) [19] equations belong to the first type of approach and their solution provides the sum of infinite classes of cluster diagrams. However, the FHNC-like summation is not complete and some diagrams, like the "elementary" ones, are not fully considered. This fact constitutes an approximation within the theory, that must be checked against known exact results, as sum rules, or compared with the outcomes of other methods. Variational Monte Carlo (VMC) [14] provides an alternative and exact, but expensive, way of completely sum the cluster contributions through stochastic evaluation of the needed many-body integrals. The integral equation method has the advantage of not being limited by the number of particles, whereas VMC becomes impractical at large A-values.

Standard perturbation theory cannot be straightly applied to the nuclear case because of the strong, nonperturbative, repulsive core. In the BBG theory