Annals of Physics 326 (2011) 566–577

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Nuclear binding energy and symmetry energy of nuclear matter with modern nucleon–nucleon potentials

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ARTICLE INFO

Article history:
Received 13 June 2010
Accepted 13 November 2010
Available online 23 November 2010

Keywords:
Symmetric nuclear matter
Equation of state
Symmetry energy
Nucleon–nucleon interaction

ABSTRACT

The binding energy of nuclear matter at zero temperature in the Brueckner–Hartree–Fock approximation with modern nucleon–nucleon potentials is studied. Both the standard and continuous choices of single particle energies are used. These modern nucleon–nucleon potentials fit the deuteron properties and are phase shifts equivalent. Comparison with other calculations is made. In addition we present results for the symmetry energy obtained with different potentials, which is of great importance in astrophysical calculation.

1. Introduction

One of the most fundamental problems in nuclear many-body theory is the attempt to evaluate the nuclear matter binding energy and saturation properties, starting from a realistic nucleon–nucleon (NN) interaction with no free parameters. In fact a lot of work has been done trying to solve this problem using different approaches and methods which are discussed in details by Müther and Polls [1]. An important ingredient of all these approaches is the consideration of the two-nucleon correlations which are induced by the strong short-range components of the NN interaction. In lowest-order Brueckner theory, the familiar Brueckner–Hartree–Fock (BHF) approach, is adopted to calculate the energy, the so-called *G*-matrix for evaluating the energy in the Hartree–Fock approach. In the *G*-matrix one accounts for the particle–particle correlations which means the scattering of two nucleons from states which are occupied in the Slatter determinant describing the ground state, into unoccupied particle states above the Fermi surface [2,3].

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doi:10.1016/j.aop.2010.11.010

The potentials we will employ here are the recent models of the Nijmegen group [4], the Argonne V_{18} potential [5] and the charge-dependent Bonn potential (CD-Bonn) [6]. The recent versions of the Nijmegen group are NijmI, NijmII and Reid 93 potentials. Although all these potentials predict almost identical phase shifts, their mathematical structure is quite different. The Argonne potential, the NijmII and the Reid 93 potentials are non-relativistic potential models defined in terms of local potential functions, which are attached to various (non-relativistic) operators of the spin, isospin and/or angular momentum operators of the interacting pair of nucleons. Such approaches to the NN potential have traditionally been quite popular since they are numerically easy to use in configuration space calculations. The NijmI model is similar to the NijmII model, but it includes also a $\mathbf{p}^2$ term, see Eq. (13) of Ref. [4], which may be interpreted as a nonlocal contribution to the central force. The CD-Bonn potential is based on the relativistic meson-exchange model of Ref. [7] which is nonlocal and cannot be described correctly in terms of local potential functions.

The nuclear matter symmetry energy, which is defined as the difference in energy per nucleon between the pure neutron matter and the symmetric nuclear matter, is an important quantity that determines the properties of objects such as the atomic nucleus and the neutron star [8]. The study of symmetry energy and its dependence on nuclear density and temperature is currently a subject of great interest [9]. Theoretically, the symmetry energy can be determined from microscopic calculations such as the self-consistent Green function (SCGF) and the Dirac–Brueckner–Hartree–Fock (DBHF) calculations, or the phenomenological calculations such as the Skyrme Hartree–Fock (SHF) and the relativistic mean field (RMF) calculations [3,8,10–12]. These calculations currently predict wide range of symmetry energies for densities below and above normal nuclear density, $\rho_0 = 0.16$ fm^{-3}. Experimentally, the symmetry energy is not a directly measurable quantity and has to be extracted indirectly from observables that are related to the symmetry energy. The experimental determination of the symmetry energy is therefore dependent on how reliable the model that describes the experimental observable is.

Recently, Li et al. [13] have studied the saturation properties of nuclear matter within the Brueckner–Hartree–Fock approach using continuous single particle energies and employing the most recent accurate nucleon–nucleon potentials. They found that their results confirm the concept of "Coester line" or "Coester band", i.e., density and energy of the various saturation points being strongly correlated, yielding either a too large saturation density or a too small binding energy.

The many-body method we will employ in deriving the EoS of both symmetric and pure nuclear matter is a rather simple one i.e., the non-relativistic BHF method with a conventional and continuous single particle spectrum using different modern NN potentials. The results in the present work which come out by approximating the single particle self-consistent potential with a parabolic form. This approximation allows to calculate the potential, at each iteration, only for few momenta, thus reducing drastically the computer time. Another aim of the present paper is therefore to investigate whether these modern phase equivalent potentials also predict differences in the symmetry energy.

2. The theoretical model

In the BHF approximation, the nuclear matter total energy E_A is obtained from the Brueckner G-matrix, $G(\omega)$, according to the equation

$$E_A = \sum_{k_1<k_F} \frac{\hbar^2 k_1^2}{2m} + \frac{1}{2} \sum_{k_1,k_2<k_F} \langle k_1 k_2 | G(e_{k_1} + e_{k_2}) | k_3 k_4 \rangle_a \tag{1}$$

with $|k_1 k_2\rangle_a = |k_1 k_2\rangle - |k_2 k_1\rangle$, i.e., the subscript a indicates antisymmetrization of the matrix elements. Here k_F is the Fermi momentum, the summation over the momenta k_i include spin and isospin variables. The single particle energies e_k, appearing in the entry energy of the G-matrix, are given by

$$e(k) = \frac{\hbar^2 k^2}{2m} + U(k) \tag{2}$$