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Isospin splitting of the nucleon-nucleus optical potential

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The volume component of the phenomenological optical potential is traced to the microscopic theory of nuclear matter. The latter is based on the Brueckner-Hartree-Fock approach with three-body force, which recently has proved to be able to reproduce the empirical saturation properties of nuclear matter. The self-energy is calculated and its on-shell matrix elements are related to the volume part of the optical potential. A previous investigation, where the real part of the microscopic potential was compared with an empirical one, which is a fit of the experimental nucleon-nucleus elastic scattering, is here extended to the absorptive component. Moreover, the isospin splitting of the optical potential is discussed in connection with the proton and neutron effective masses of isospin asymmetric nuclear systems.

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I. INTRODUCTION

In a brief report [1] (hereafter referred to as Ref. [1]) the theoretical description of the nucleon-ion optical model potential (OMP), developed in the 1970s [2], was revisited in view of recent numerical developments of the microscopic theory of nuclear matter. The latter in fact was proved to be able to predict the empirical saturation properties in the framework of the Brueckner approach with two-body force plus three-body force (TBF) (see Ref. [3] and references therein). On the empirical side, the existence of powerful fits of experimental nucleon-nucleus cross sections for a large amount of nuclei permits us to constrain the corresponding theoretical observables, leaving only a small room to uncertainties.

In Ref. [1] the volume term of Köning and Delaroche (KDR) optical model potential (OMP) parametrization [4], based on the fit of the nucleon-nucleus scattering data, was compared with the on-shell self-energy, calculated in Brueckner-Hartree-Fock (BHF) approximation with TBF. A special emphasis was put on the isospin splitting of neutron vs. proton optical potential as a constraint on the isovector part of the nucleon-nucleon interaction. The opportunity offered by the huge number of experimental data available in a large range of energy, 0–200 MeV, and asymmetry $\beta = \frac{N-Z}{A}$, made it possible to perform such a study. The hope is that the theoretical outputs can provide reliable predictions for the physics with radioactive ion beams (RIB) probing a broad range of isospin, including structure as well as dynamical effects. In this article we discuss to a larger extent the same subject, including the numerical estimate of the absorption process along with a comparison with the KDR parametrization and some important properties of the isovector potential such as the isospin splitting of the effective mass [5]. To pursue such a purpose the theoretical description of the single-nucleon properties was based on the so called extended Brueckner-Hartree-Fock (EBHF) approximation [6,7]. EBHF is in fact an approximation beyond the mean-field limit, because it incorporates the effects of ground-state correlations resulting into a smearing out of the Fermi surface. The quantitative estimate of this effect has been refined by means of the application of the Hughenoltz-Van Hove (HVH) theorem [8]. In such a context a complete theoretical description of the OMP is possible and conclusions can be drawn on the capability of the Brueckner theory of reproducing the experimental data and on possible future developments.

II. REVIEW OF THE EBHF APPROXIMATION FOR THE NUCLEON SELF-ENERGY

In this section we review the properties of the self-energy in the framework of the Brueckner theory with TBF [7,9,10] of asymmetric nuclear matter. For a nucleon of isospin τ and momentum k the single-particle (s.p.) energy $\epsilon_\tau(k)$, is determined, according to the Landau-Migdal theory, by the functional derivative of the energy per particle E_A with respect to the occupation numbers $n_\tau(k)$, namely

$$\epsilon_\tau(k) = \frac{\delta E_A}{\delta n_\tau(k)}. \tag{1}$$

This equation permits us to derive from a given approximation to E_A the corresponding $\epsilon_\tau(k)$ in a consistent way. In the case of the Brueckner theory the self-energy expansion consistent with the one-loop approximation for the energy shift (BHF) was developed and named extended Brueckner Hartree-Fock. In the first version it included only the two-body force [7], but later it was extended to include TBF rearrangement terms

[10]. The TBF was proved to be essential for reproducing the empirical saturation point. Within the EBHF approximation the main contributions to the self-energy, derived from Eq. (1), are

$$\Sigma_\tau(k,\epsilon) = \Sigma_\tau^{\rm bhf}(k,\epsilon) + \Sigma_\tau^{\rm cpol}(k,\epsilon) + \Sigma_\tau^{\rm tbf}(k)\cdot \qquad (2)$$

In general, the self-energy is a complex quantity that is energy and momentum dependent. The physical meaning of the real part is as follows. The first term is the contribution of the inert core, i.e., the self-consistent mean-field potential with G matrix as effective interaction; the second one is the contribution of the core polarization; and the third one stems from the density dependence of effective TBF [10]. The imaginary part of the self-energy $\Sigma_\tau^{\rm bhf}(k,\epsilon)$ describes the process of promoting a particle to a state above the Fermi surface, accompanied by particle-hole (ph) excitations and it is nonvanishing only for $k > k_F$. The imaginary part of $\Sigma_\tau^{\rm cpol}(k,\epsilon)$ describes the promotion of a particle to a hole state, accompanied by ph excitations and it is nonvanishing only for $k < k_F$. The last term, $\Sigma_\tau^{\rm tbf}$, in our approximation is real, being directly related to the TBF. For positive energies only the first process contributes to absorption.

The self-energy, approximated by Eq. (2), misses some contributions (diagrams beyond the second order in G-matrix expansion); thus it does not fulfill with great accuracy the HVH theorem. These contributions introduce ground-state correlations that amount to a depletion of the Fermi distribution appearing in the self-energy integrals. This correction can be imposed by introducing a suitable depletion factor κ so that the total self-energy, Eq. (2), is replaced by the following one:

$$\Sigma_\tau = (1-\kappa_\tau)\left(\Sigma_\tau^{\rm bhf} + \Sigma_\tau^{\rm cpol} + \Sigma_\tau^{\rm tbf}\right). \qquad (3)$$

The parameter κ is intimately related to the wound parameter, which controls the convergence of the Brueckner hole-line expansion [6]. The correction can be directly evaluated from the three and four hole line self-energy diagrams [6,7]. But because κ is only sensitive to the Fermi surface, we can alternatively extract its value from the HVH theorem [8]. In the general case of asymmetric nuclear matter at the density $\rho = A/V$ with proton fraction $Y_p = Z/A$ and neutron fraction $Y_n = N/A$, the HVH theorem is written as

$$E_A + \frac{p}{\rho} = \sum_\tau Y_\tau \epsilon_\tau^F \qquad (4)$$

$$\epsilon_\tau^F = \frac{\left(k_\tau^F\right)^2}{2m} + \Sigma_\tau\left(k_\tau^F\right), \qquad (5)$$

where E_A is the energy per particle, p the pressure, ϵ_τ^F and k_τ^F the Fermi energy, and Fermi momentum, respectively, for the nucleon τ. For small isospin asymmetry β, which is our case indeed, $\kappa_n - \kappa_p$ is quadratic in β, and thus in the calculation κ_τ was assumed to be independent of isospin. The value of κ_τ, which is density dependent, was estimated around 0.173 at the saturation density $\rho = 0.17$ fm^{-3}.

III. OMP FROM THE BHF APPROXIMATION

A. Microscopic definition of OMP

Let us consider a nucleon with isospin τ traveling inside nuclear matter with energy E and momentum k. The real part of the microscopic optical model potential U_τ is defined as the real part of on-shell self-energy,

$$U_\tau(E) = \Re\Sigma_\tau[E, k(E)], \qquad (6)$$

where E is the energy of the projectile and $k(E)$ is the corresponding momentum. Both are real and fulfill the mass-shell relation

$$E = \frac{k^2}{2m} + \Re\Sigma_\tau(E,k)\cdot \qquad (7)$$

The absoption part of the microscopic optical model potential W_τ is related to the imaginary part of the self-energy. In the presence of absorption, the relation between the energy E, which is still real, and momentum, which now is complex, is the complex mass-shell relation

$$E = \frac{k^2}{2m} + \Sigma_\tau(E,k)\cdot \qquad (8)$$

The absorption part W is identified with the imaginary part of momentum. Assuming $E - U \gg W$, which is satisfied in the energy range under consideration [9], we find

$$W_\tau(E) = \frac{m_k^*}{m}\Im\Sigma(E), \qquad (9)$$

where W is obtained by expanding the self-energy up to the first order in the single-particle energy (see Ref. [11] and references therein). In nuclear matter there is no Coulomb force between charged particles, but in the comparison with experimental data of finite nuclei we must introduce the Coulomb correction into the proton OMP. According to Ref. [11], this is given by the following prescription

$$\Sigma_p^c(E) = \Sigma_p(E - V_c) + V_c \qquad (10)$$

as also discussed in Ref. [1]. V_c denotes the Coulomb force. From now on the Coulomb correction is understood.

B. Isospin splitting of OMP and effective mass

In asymmetric nuclear matter the OMP can be split into isoscalar and isovector components. Because one expects a linear dependence on the isospin parameter (Lane potential [12]), it is convenient to introduce the symmetry potential defined as follows

$$U_{\rm sym}(E) = \frac{U_n(E) - U_p(E)}{2\beta} \qquad (11)$$

$$W_{\rm sym}(E) = \frac{W_n(E) - W_p(E)}{2\beta}, \qquad (12)$$

for the real and imaginary parts, respectively. The isospin splitting of the OMP is directly related to the isospin splitting of the effective mass, as it can be easily shown

$$2\beta\frac{dU_{\rm sym}(E)}{dE} = \frac{m_p^* - m_n^*}{m}. \qquad (13)$$

Therefore, the energy slope of the $U_{\rm sym}(E)$ can predict the sign of the proton vs. neutron effective mass isospin splitting. There has been much speculation on this issue for its implications in heavy-ion dynamics [13]. Because the effective mass depends also on the energy, it is possible that the splitting changes sign going from low to high energy. There is some theoretical indication that this could indeed be the case (see below).

C. Numerical results

In the present Brueckner calculations we adopt a recent version of a realistic interaction, where the two-body force and TBF are built up within the one-boson exchange (OBE) approximation of the meson exchange model for the interaction [3]. The same meson parameters are used in the interaction vertices of both two- and three-body forces. The parameters were taken from the Bonn B potential, which fits the experimental NN phase shifts [14]. Comparing with previous BHF calculations with TBF [15,16], the present interaction reproduces quite well the empirical saturation point, i.e., $E_A \approx -16$ MeV and $\rho \approx 0.17$ fm^{-3}, whereas the two-body force overestimates to a large extent the saturation density [3]. Other important saturation properties such as the compression modulus and symmmetry energy are reproduced as well [3,17]. Because the volume term crucially depends on the saturation density, the calculation with only a two-body force, as, for instance, the Reid soft core potential, adopted in Ref. [2], is expected to be very different from that including TBF.

The complex self-energy is shown on the left-hand side of Fig. 1 for some values of the asymmetry parameter. In the upper panel it is plotted the real part of the self-energy. It is worthwhile noticing that increasing the neutron number ($\beta > 0$) the proton potential tends to be more and more attractive and the neutron one less and less in the lower energy range, whereas the opposite trend starts to manifest itself at higher energy. Both effects can be clearly seen in Fig. 2. In the lower panels the imaginary part of self-energy is plotted. In the considered energy range only $\Sigma_\tau^{\rm bhf}$ contributes, as noted in Sec. II. It is monotonically increasing in absolute value with energy because, as expected, while the energy increases, deeper and deeper levels are involved in the particle-hole excitation process. The deepening of the proton spectrum with increasing isospin is also the explanation of the increasing of W_p with isospin. The other way around occurs for W_n. In the right-hand side of Fig. 1 the real part of the on shell self-energy vs. energy in symmetric nuclear matter is depicted along with its three components, Eq. (2). In the considered energy range the value of U is mostly determined by the interplay between the attractive $\Sigma_\tau^{\rm bhf}$ and the repulsive $\Sigma_\tau^{\rm tbf}$, the core polarization contribution being small above the Fermi energy. The depth at zero energy must be compared with the empirical potential used to study the structure of nuclei.

The isovector splitting of the potential is shown in Fig. 2 and Fig. 3 as a function of energy and isospin. One main feature of both the real and imaginary parts that must be emphasized is the linear isospin dependence, which is pretty well respected in the whole energy range in accordance with the phenomenological Lane potential [12]. The energy dependence of $U_n - U_p$ brings information on the isospin splitting of the effective mass, as expressed by Eq. (13). Looking at the energy slope one may conclude that the isospin splitting of neutron to proton effective mass is such that the neutron effective mass increases with isospin, whereas the proton effective mass decreases. As noted, the three curves cross at $E \approx 180$ MeV marking a sign inversion in the isospin dependence. This inversion is accompanied by a softer energy slope indicating a possible equalization of the two effective masses at higher energy. The strong influence of the neutron and proton effective masses in the transport model simulations of heavy-ion collisions at relativistic energies [13] demands for exploring a broader energy range. However, this task is made difficult by the lack of realistic interactions able to fit the experimental NN phase shifts at high energy.

In our approximation, the imaginary part of isovector potential $W_n - W_p$ is composed of two terms [see Eq. (2)].

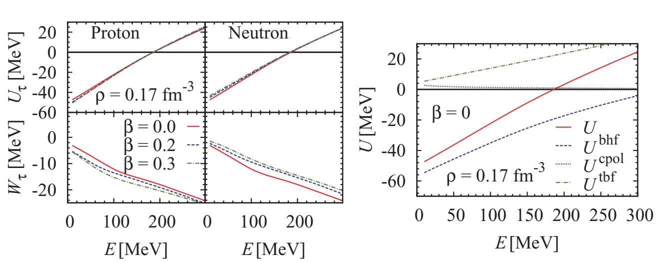

FIG. 1. (Color online) (Left) On-shell self-energy $\Sigma_\tau = U_\tau + iW_\tau$ vs. energy for nuclear matter at the saturation density. (Right) The three partial contributions of $U(E)$ [see Eq. (2) in the text] for symmetric nuclear matter.

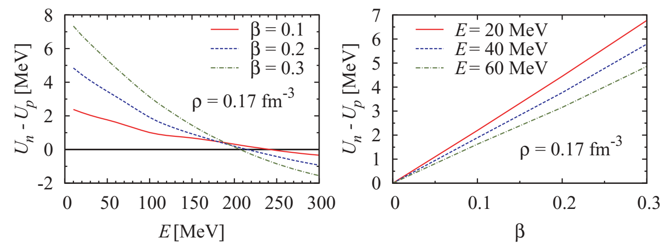

FIG. 2. (Color online) Isospin splitting of the real part of the microscopic OMP vs. energy (left) and symmetry parameter (right).

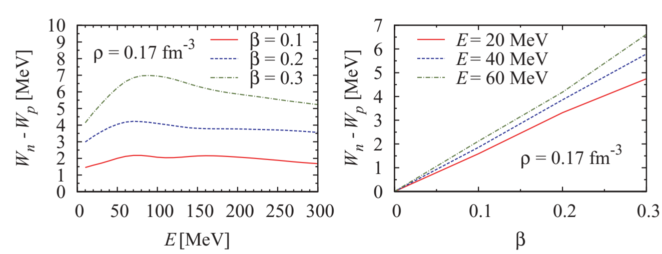

FIG. 3. (Color online) Isospin splitting of the imaginary part of the microscopic imaginary OMP vs. energy (left) and symmetry parameter (right).

In the continuum the contribution due to the core polarization term vanishes. Looking at its energy dependence, $W_n - W_p$ first increases at low energy; it tends to stabilize to a constant value depending on isospin only.

IV. PHENOMENOLOGICAL OMP AND COMPARISON WITH THEORY

The nucleon-nucleus collisions are described by phenomenological optical model potentials or by nucleon-nucleon interactions folded with target density. It is customary to split the phenomenological OMP into the following components

$$V(r, E) = V_{\rm vol} + V_{\rm SO}\,(\vec{l}\cdot\vec{\sigma}) + V_D + V_C, \tag{14}$$

where $V_{\rm vol}$, $V_{\rm SO}$, V_D are volume, spin-orbit, and surface terms, respectively, and V_C is the Coulomb contribution of protons. $V_{\rm vol}$ and V_C are essentially volume terms, whereas $V_{\rm SO}$ and V_D are surface terms. As in Ref. [1], we consider for our investigation the parametrization of Ref. [4], which is able to fit a huge number of n-A and p-A collisions into a broad range of energies, i.e., $0 < E < 200$ MeV. In this parametrization the strengths are disentangled from the r-dependent form factors. This is a desirable feature, because in nuclear matter we can only determine the strengths, in particular only the strength of the volume term $V_{\rm vol}$, which in any case brings a lot of information on the energy and isospin-asymmetry dependence. Following the KDR model we write

$$V_{\rm vol}(r, E) = \frac{V_{\rm vol}(E)}{1 + e^{(r-R_i)/a_i}}, \tag{15}$$

where $R_i = r_i A^{1/3}$ is the nuclear radius and a_i is the diffuseness parameter. Thus $V_{\rm vol}(E)$ can be directly related to the nuclear matter self-energy. Moreover, as shown in Ref. [4], it provides the most sizable contribution to the optical potential in the energy range up to 200 MeV. Its energy dependence is expressed as polynomial expansion around the Fermi energy ϵ_F ($n = 4$) for the real part

$$\Re V_{\rm vol}(E) = \sum_{k=1,n} v_k (E - \epsilon_F)^{k-1} \tag{16}$$

and as Lorentzian shape for the imaginary part

$$\Im V_{\rm vol}(E) = w_1 \frac{(E - \epsilon_F)^2}{(E - \epsilon_F)^2 + w_2^2} \tag{17}$$

In the KDR model [4] a local (i.e., one by one), as well as a global fit of the experimental nucleon-ion cross sections was performed. We only focus on the local fit for the purpose of a direct comparison between a microscopic theory and a phenomenological approach. Looking at the empirical data plotted in Fig. 4 the empirical optical potential is shown in comparison with the above described theoretical estimates. In the upper panels one can see that, for the real part, the agreement with theory is pretty good both for the magnitude and for the isospin dependence. The agreement is better for the heaviest nuclei where the central density better realizes the nuclear matter saturation density. One has to bear in mind that there are no adjusted parameters in the theoretical values. In the lower panels the absorption term is reported. At variance

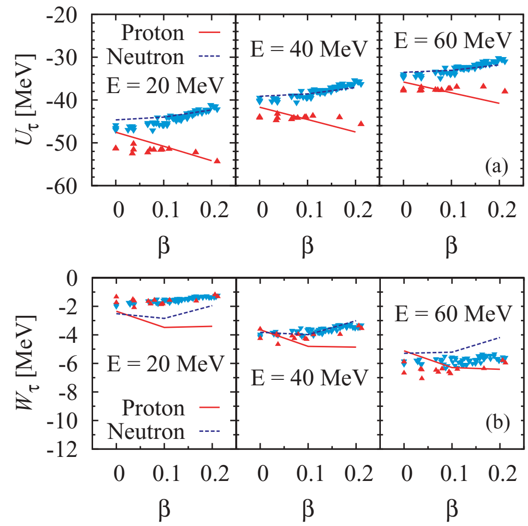

FIG. 4. (Color online) Volume term of the empirical optical potential for nuclei in comparison with the theoretical nuclear matter BHF predictions. U_τ and W_τ denote the real and imaginary parts, respectively. The symbols correspond to nuclei, ^{28}Si to ^{208}Pb, from left to right. The theoretical proton OMP is Coulomb corrected.

with the theory the empirical points do not exhibit any isospin splitting. But, as expected theoretically, the isospin resolution is of the same order of magnitude as the uncertainty in the fit already mentioned in Ref. [4]. The latter was estimated of the order of 10%, related to the more difficult measurement of the reaction cross sections.

An unpleasant feature is that the theoretical values of $W^{\rm bhf}$ overestimate, at least at low energy, the empirical values, whereas one expects that our theoretical model cannot exhaust all the absorption mechanisms present in the real experiments. There are two approximations at the origin of these results: the first is the assumption of a density equal to maximum, given by the saturation value; the second approximation is that of neglecting the Pauli principle. These two points deserve further investigation.

A more detailed study of the energy dependence is reported in Fig. 5 for three nuclei corresponding to $\beta = 0.0, 0.11, 0.22$, respectively. The empirical values of OMP for elastic scattering are quite well reproduced by the theoretical predictions.

As to the real component U_τ, a deviation is observed both for neutrons and protons in ^{28}Si, for which the approximation of constant density is less appropriate. In the panels for the proton OMP the values with and without Coulomb correction are depicted. The overall agreement of empirical OMP with the theoretical predictions supports the above-discussed theoretical prediction that the neutron vs. proton isospin splitting is such that the neutron effective mass turns out to be larger than the proton one.

As to the absorption component W_τ, a general feature is that the theoretical OMP values underestimate the empirical data, especially at higher energy. As already mentioned, this is an indication that inelastic channels present in the experimental cross sections, e.g., multiple p-h excitations or three body contributions, are absent in our approximation. This point deserves further consideration. The empirical W_p is much

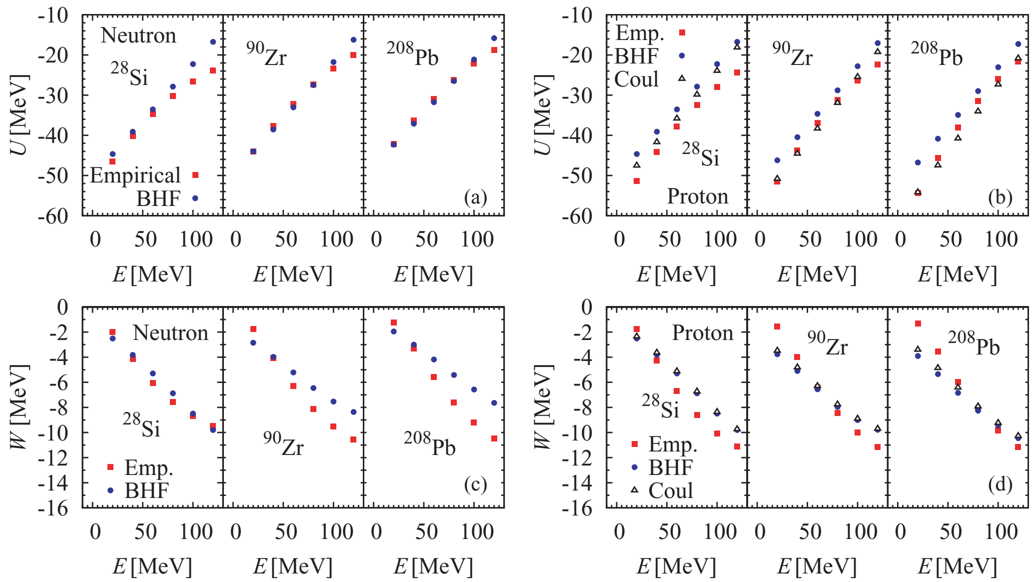

FIG. 5. (Color online) Volume term of OMP vs. energy for neutron-ion elastic scattering (upper panel) and absorption (lower panel).

better reproduced, perhaps due to the Coulomb barrier that hinders some absorption channels. In conclusion, in view of the fact that in our calculation there are not adjusted parameters, the agreement with the empirical KDR fit is quite satisfactory, and it could be a good starting point for a deeper investigation of the theory of nucleon-nucleus collisions.

V. DISCUSSION AND CONCLUSIONS

In the present note we have revisited the theoretical background of the nucleon-nucleus OMP for elastic scattering and absorption based on a microscopic theory of nuclear matter. Because in nuclear matter there is neither surface nor spin-orbit contribution, only the volume term of the OMP was considered. The Coulomb force cannot be included either. Nevertheless this volume term is by far the most important contribution to OMP, not only at low energy but also at energy as high as 200 MeV.

The theoretical approach adopted in this study is the Brueckner theory, which traces the properties of nuclear matter back to the experimental NN scattering via the introduction of realistic interactions. Using as a realistic interaction a two-body force plus TBF in a unified meson exchange model [3] within the BHF approximation, it was possible to reproduce not only the empirical saturation point of nuclear matter but also to fulfill the HVH theorem. The latter, in fact, guarantees the consistency between the approximations in the hole line expansion for the energy shift and the hole line expansion for the self-energy.

The real and imaginary parts of the on-shell nucleon self-energy, which is the microscopic quantity underlying the empirical OMP, have been calculated in the BHF approximation with TBF. The contributions to the self-energy, which are consistent in the HVH sense (i.e., in the EBHF approximation), take into account mean field, core polarization, and three-body force rearrangement terms.

The self-energy was calculated at the nuclear saturation density and isospin range typical of the considered nuclei. The isovector potential was calculated vs. momentum and energy, and it was found to be in agreement with the Lane potential [12]. It was shown that the energy dependence of the isovector potential is related to the isospin splitting of the neutron and proton effective masses. In the low-energy range the isovector potential is decreasing with energy, indicating that the neutron effective mass is larger than the proton one at finite isospin. On the other hand, at some energy the isovector potential vanishes and then changes sign indicating a possible change in the effective mass isospin spitting. Due to the strong interest for the effective mass in high-energy heavy-ion collisions, the latter feature asks for high momentum and energy microscopic calculations of the self-energy with realistic interaction fitting high-energy nucleon-nucleon scattering phase shifts.

The comparison between the microscopic OMP, obtained from the on-shell self-energy, and the empirical one from the KDR fit, was performed. To such a purpose the Coulomb corrections were imposed to the proton self-energy. Considering that there is no adjusted parameter in the theoretical values, the behavior in energy and isospin of the empirical OMP for elastic scattering is quite well reproduced by the theory. The agreement is also satisfactory for the magnitude of the absorption part, but the empirical absorption does not show a clear isospin splitting. The good agreement in the energy dependence of $U_n(E)$ and $U_p(E)$ supports the theoretical prediction that the neutron effective mass becomes larger than the proton one increasing isospin, at least in the considered energy range. But, because the effective mass is itself energy dependent, additional investigation is required, as we stressed before, to study isospin effects at high energy, above 200 MeV.

The results presented in this article together with those of Ref. [1] encourage us to further develop our investigation on the OMP and its microscopic grounds. First, the calculation will be extended to a range of densities beyond the saturation value, so to get a density-dependent OMP to be used for finite nuclei within the local density approximation. Second, the comparison of the theoretical isovector potential will be extended to the fit of charge exchange reactions [18]. This investigation points to further probe the spin-isospin vertex of the nuclear interaction, after the successful test with the Gamow-Teller resonance [19]. Third, from a suitable folding of the volume term one can build up the nucleus-nucleus OMP to describe heavy-ion collisions, including the fusion of heavy and super heavy elements where still phenomenological OMP models are used [20]. The extension to the nucleus-nucleus potential would be of some interest also in the fit of elastic-scattering data with a halo projectile [21].

Finally, it would be desirable to calculate within the same microscopic approach also the spin-orbit contribution, a long-term task that seems to be viable after the inclusion of relativistic effects (virtual nucleon-antinucleon excitations) [1] into the Brueckner theory in the form of TBF.

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