Isospin dependence of nucleon-nucleon elastic cross section

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The in-medium neutron-proton, proton-proton (neutron-neutron) scattering cross sections (σ_{np}, σ_{pp(nn)}) are studied based on QHD-II type Lagrangian within the framework of the microscopic transport theory. The results demonstrate that, for free nucleon-nucleon scattering cross sections, the isospin dependence is dominantly caused by ρ meson field. The medium correction of nucleon-nucleon scattering cross sections is also isospin dependent, σ_{np} depends on the baryon density weakly and σ_{pp(nn)} depends on the baryon density significantly, which is due to the different effects of the medium correction of nucleon mass and ρ meson mass on σ_{np} and σ_{pp(nn)}, respectively.

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I. INTRODUCTION

With the establishment of secondary beam facilities at many laboratories around the world, the experimental studies of collisions of nuclei with large neutron or proton excess have become available, which opens up a new field of study on the structure of nuclei far from the stability line and nuclear reaction and the reaction mechanism at extreme of asymmetric nuclear matter. In order to study the isospin dependence of the multifragmentation nuclear reaction and the reaction mechanism at extreme of the in-medium elastic nucleon-nucleon cross sections. In Sec. III we give the numerical results for both free and in-medium nucleon-nucleon cross sections. Finally, a brief summary is given in Sec. IV.

II. FORMALISM

We start with the QHD type effective Lagrangian, in which the interaction between nucleons is described by exchanges of σ, ω, π, and ρ mesons. In Ref. [11], the contribution from isovector ρ meson field is neglected, while in this work the contribution of ρ mesons has to be considered because it plays a major role in the isospin dependence of the interaction. The Lagrangian under consideration reads as

\[ L = L_F + L_I. \]

Here \( L_F \) is the Lagrangian density for free nucleon and meson fields.

\[
\begin{align*}
L_F &= \bar{\Psi} [i \gamma_\mu \partial^\mu - M_N] \Psi + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&\quad + \frac{1}{2} \partial_\mu \pi \partial^\mu \pi - \frac{1}{4} L_{\mu\nu} L^{\mu\nu} - U(\sigma) + U(\omega) - U(\pi) \\
&\quad + U(\rho), \end{align*}
\]

where

\[
F_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu.
\]

and

\[
L_{\mu\nu} = \partial_\mu P_\nu - \partial_\nu P_\mu.
\]

\( U(\sigma), U(\omega), U(\pi), \) and \( U(\rho) \) are the self-interaction parts of the \( \sigma, \omega, \pi, \) and \( \rho \) meson fields and the respective expressions are

\[
U(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{3} b \sigma^3 + \frac{1}{4} c \sigma^4,
\]

\[
U(\omega) = \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu.
\]
\[ U(\tau) = \frac{1}{2} m^2 \mathbf{p}^2. \] (7)

\[ U(p) = \frac{1}{2} m^2 p^2. \] (8)

\( L_I \) is the interaction Lagrangian density of nucleons coupled to \( \sigma, \omega, \pi, \) and \( \rho \) mesons and reads as

\[ L_I = g_a \bar{\psi} \gamma^\mu \gamma^\nu \psi \partial_\mu \partial_\nu + g_\sigma \bar{\psi} \gamma^\mu \gamma^5 \psi \partial_\mu \pi + g_\omega \bar{\psi} \gamma^\mu \gamma^5 \psi \partial_\mu \omega + g_\rho \bar{\psi} \gamma^\mu \gamma^5 \psi \partial_\mu \rho. \] (9)

where a pseudovector coupling is adopted for pion-nucleon coupling and \( g_\pi = -f_\pi/m_\pi. \)

It is convenient to make use of the closed time-path Green’s function technique. The nucleon Green’s function in the interaction picture can be defined by

\[ iG_{12} = \langle T[\exp(-i \int dx H_I(x))\Psi(1)\Psi(2)] \rangle. \] (10)

Here 1, 2 represent the 4-dimension coordinates of two states, which we define on a time loop [8]. The corresponding Dyson equation for \( iG_{12} \) is

\[ iG_{12} = iG_{12}^0 - \int dx_3 \int dx_4 G_{14}^0 \Sigma(4,3) iG_{32}. \] (11)

The nucleon self-energy \( \Sigma(4,3) \) considering up to Born term reads as

\[ \Sigma(4,3) = \Sigma_{HF}(4,3) + \Sigma_{\text{Born}}(4,3), \] (12)

where the Hartree-Fock term \( \Sigma_{HF}(4,3) \) contributes to the mean field and the Born term \( \Sigma_{\text{Born}}(4,3) \) contributes to the binary collision part. After making a Wigner transformation on both sides of equation of motion for \( G^{-1} \) and then adopting the semiclassical and quasiparticle approximation, we finally get the self-consistent RBUU equation for the nucleon’s distribution function [8].

\[ \Sigma_{HF}(\rho)(x,\tau) = \left\{ \begin{array}{ll} \frac{g^2}{m^2} \frac{1}{2(2\pi)^3} \int d^3 p \frac{p^\mu}{(p^2 + M^*)^{1/2}} \left[ f\left(x,p,\frac{1}{2}\right) - f\left(x,p,-\frac{1}{2}\right) \right], & \tau = \frac{1}{2}, \\
\frac{g^2}{m^2} \frac{1}{2(2\pi)^3} \int d^3 p \frac{p^\mu}{(p^2 + M^*)^{1/2}} \left[ f\left(x,p,-\frac{1}{2}\right) - f\left(x,p,\frac{1}{2}\right) \right], & \tau = -\frac{1}{2}, \end{array} \right. \] (18)

Here \( M^* \) denotes the effective mass of nucleon. Because \( \pi \) is a pseudoscalar meson there is no contribution from \( \pi \) meson to the Hartree term and for \( \rho \) meson, only the third component of \( \rho \) meson field contributes to the Hartree term since there is no charge exchange at the Hartree level. The Hartree terms given in Eqs. (16), (17), and (18) should be solved self-consistently with the field equations of \( \sigma, \omega, \) and \( \rho \) mesons. The Fock terms are usually neglected in the transport theory approach for simplicity.

The right-hand side of Eq. (13) is the collision term derived from the same Lagrangian as that of mean field, which we will stress in this paper.
Here we only calculate the elastic part, which can be written as

\[
C_{el}(x, p, \tau) = 1 \int \frac{d^3p_2}{(2\pi)^3} \int \frac{d^3p_4}{(2\pi)^3} \int \frac{d^3p_1}{(2\pi)^3} \delta^4(p + p_2 - p_3 - p_4) \\
\times W_{el}(p, p_2, p_3, p_4)[F_2 - F_1],
\]

where \( W_{el}(p, p_2, p_3, p_4) \) is the transition probability. The relation between the transition probability and differential cross section is

\[
\int \nu \sigma_{el} d\Omega = \int \frac{d^3p_1}{(2\pi)^3} \frac{d^3p_4}{(2\pi)^3} \delta^4(p + p_2 - p_3 - p_4) \\
\times W_{el}(p, p_2, p_3, p_4).
\]

Inserting Eq. (21) into Eq. (20) we obtain

\[
C_{el}(x, p, \tau) = 1 \int \frac{d^3p_2}{(2\pi)^3} \int \frac{d^3p_4}{(2\pi)^3} \delta^4(p + p_2 - p_3 - p_4) \\
\times W_{el}(p, p_2, p_3, p_4)[F_2 - F_1],
\]

where \( \nu \) is the Møller velocity and \( \sigma_{el} \) is the elastic differential cross section. \( F_1 \) and \( F_2 \) are the Pauli block factors, which can be written as

\[
F_1 = f_1(x, p, \tau)f_2(x, p, \tau)[1 - f_3(x, p, \tau)][1 - f_4(x, p, \tau)],
\]

\[
F_2 = f_3(x, p, \tau)f_4(x, p, \tau)[1 - f_1(x, p, \tau)][1 - f_2(x, p, \tau)].
\]

The detailed expressions of the proton-proton, neutron-neutron, and neutron-proton cross sections are given as follows:

\[
\frac{d\sigma_{pp}}{d\Omega} = \frac{d\sigma_{nn}}{d\Omega} = \sum_{i=1}^{10} A_i [D_i(s, t) + E_i(s, t, u) + (s, t \rightarrow u)],
\]

\[
\frac{d\sigma_{np}}{d\Omega} = \sum_{i=1}^{10} A_i [d_i D_i(s, t) + e_i E_i(s, t, u) + (s, t \rightarrow u)],
\]

where \( i \) denotes the contributions from individual \( \sigma, \omega, \pi, \rho \) exchange and crossing terms. The coefficients \( A_i, i = 1, 10 \) are

\[
A_1 = \frac{1}{(2\pi)^2} \frac{g_4^2}{s^2}, \quad A_2 = \frac{1}{(2\pi)^2} \frac{g_\omega^4}{s},
\]

\[
A_3 = \frac{1}{(2\pi)^2} \frac{M^*}{M_N} \frac{g_4^2}{s^2}, \quad A_4 = \frac{1}{(2\pi)^2} \frac{g_\omega^4}{s^2}.
\]

The coefficients \( d_i, e_i \), in Eq. (26) are given as

\[
d_1 = d_2 = d_3 = 1, \quad d_4 = d_9 = d_{10} = 0,
\]

\[
d_7 = d_8 = -1,
\]

\[
e_1 = e_2 = e_5 = 0, \quad e_3 = e_4 = e_{10} = -4, \quad e_6 = e_7 = e_8 = e_9 = 2,
\]

and the expressions of \( D_i, E_i \), read as

\[
D_1 = \frac{(t - 4M^* s)^2}{2(t - m^2)^2}, \quad E_1 = \frac{t(s + 4M^* s - 9(t - 16M^* s))}{8(t - m^2)^2},
\]

\[
D_2 = \frac{2s^2 + 8st + 28M^* s + 16M^* 4}{(t - m^2)^2},
\]

\[
D_3 = \frac{i^2}{2(t - m^2)^2}, \quad E_3 = \frac{(4M^* s - 5st)}{8(t - m^2)^2},
\]

\[
D_4 = D_5(m \rightarrow m'), \quad E_4 = E_5(m \rightarrow m'),
\]

\[
D_5 = \frac{(4s^2 + 8M^* 2s + 24M^* 4)}{4(t - m^2)^2}, \quad E_5 = \frac{(t - 4M^* s - 10M^* 2s + 24M^* 4)}{4(t - m^2)^2},
\]

\[
D_6 = 0, \quad E_6 = \frac{(t + s)^2 8M^* 2s + 16M^* 4}{8(t - m^2)^2},
\]

\[
D_7 = D_7(m \rightarrow m'), \quad E_7 = E_7(m \rightarrow m'),
\]
common used form factor of nucleon-meson-nucleon vertex, have to make some preparations. First, we introduce the mean field approximation, one can easily find that the direct nucleon-nucleon cross sections, which are beyond the change vertex and cancellation between the terms corresponding to \( \sigma \) and \( \omega \) is lost. Therefore they become very sensitive to \( g_\sigma \) and \( g_\omega \). Figure 1 shows the calculated \( n-p \) scattering cross sections from the contributions of \( \sigma \) and \( \omega \) field with parameter sets given in Table I comparing with the experimental data taken from [7].

The parameter sets for \( \sigma \) and \( \omega \) given in Table I are taken from [12,11], \( g_\rho \) is taken from [13] by fitting the symmetry energy of the ground state of asymmetric nuclear matter, and a common used value is taken for the coupling constant \( g_\pi \). From the figure we can see that there is a marked different behavior of cross sections with different sets of coupling constants. It means that the nucleon-nucleon cross sections are indeed very sensitive to the coupling constants \( g_\sigma \) and \( g_\omega \). Because the main contribution to the cross section comes from \( \sigma \) meson at low energy and \( \omega \) meson at high energy, if \( g_\omega \) is much larger than \( g_\sigma \), the cross section will rise too fast with the increase of energy as shown by the curve calculated with set 6 in the figure. After studying the behavior of cross sections as a function of energy with at least 30 sets of the coupling constants taken from [12,11,14] we find if \( g_\omega > g_\sigma \) and \( g_\omega g_\sigma < 2 \) the tendency of \( \sigma_{\text{free}}^{\text{pp(\pi\pi)}} \) and \( \sigma_{\text{free}}^{\text{np(nn)}} \) with increasing energy is approximately to that of experimental data. In the following calculation, the param-

![Graph](image.png)

**FIG. 1.** The free nucleon-proton scattering cross sections where only the contributions of \( \sigma \) and \( \omega \) are taken into account. The parameter sets used are given in Table I. The experimental data are also given in the figure.


table I. Parameter sets.

| \( g_\sigma \) | \( g_\omega \) | \( b \) [fm]^{-1} | \( c \) | \( m^* \) | \( K \) [MeV] | \( E_{	ext{th}} \) [MeV] | \( \rho_0 \) [fm]^{-3} |
|---|---|---|---|---|---|---|---|
| Set 1 | 5.93 | 6.70 | 67.98 | 523.06 | 0.85 | 400 | -16 | 0.15 |
| Set 2 | 8.94 | 9.60 | -11.19 | 25.47 | 0.75 | 300 | -16 | 0.15 |
| Set 3 | 9.40 | 10.95 | -0.69 | 40.44 | 0.70 | 380 | -15.57 | 0.145 |
| Set 4 | 6.90 | 7.54 | -40.49 | 383.07 | 0.83 | 380 | -15.76 | 0.145 |
| Set 5 | 7.24 | 7.34 | -39.14 | 696.71 | 0.85 | 200 | -15.75 | 0.1484 |
| Set 6 | 11.31 | 15.30 | -35.84 | 596.18 | 0.70 | 200 | -15.75 | 0.1484 |
the ratio between the calculated and experimental ones. We can see that the parameter set 4 is taken because a best fit to the experimental data shown in Fig. 1, which is consistent with [11]. Figure 2 shows the ratio of the calculated $\sigma_{np}^{free}$ to $\sigma_{pp(nn)}^{free}$ as a function of $s^{1/2}$ as well as that of the corresponding experimental ones. We can see that the ratio between the calculated $\sigma_{np}^{free}$ and $\sigma_{pp(nn)}^{free}$ contributed only from $\sigma$ and $\omega$ mesons is about unity and far from the experimental ratio especially at low energy. However, $\rho$ meson plays major role in the isospin dependence of the nucleon-nucleon interaction, we then consider the contributions of $\pi$ and $\rho$ mesons. We find that the contribution from $\pi$'s is very small, only about several millibarons, and $\rho$ meson provides the dominant contribution to the isospin dependence of the nucleon-nucleon scattering cross sections. The $\rho-\sigma$ and $\rho-\omega$ crossing terms $D_7$ and $D_9$ give the largest contribution. The contribution of $D_7$ term to $\sigma_{np}$ is positive and is negative to $\sigma_{pp(nn)}$ . The contribution of $D_9$ to $\sigma_{pp(nn)}$ and to $\sigma_{np}$ is opposite to $D_7$. But the magnitude of $D_7$ is larger than that of $D_9$ so the net contribution of them enhances $\sigma_{np}^{free}$ and suppresses $\sigma_{pp}^{free}$. Figures 3(a) and 3(b) show the experimental and calculation results of $\sigma_{np}^{free}$ and $\sigma_{pp(nn)}^{free}$, respectively. The general behavior of the isospin dependence of nucleon-nucleon scattering cross sections is in consistent with the experimental data, though the theoretical calculation results are a little larger than those from experiments. The parameters of Walecka model are originally fixed by the saturation properties of nuclear matter. It is not clear what values of the parameters there should be in free space. From the DBHNF calculation of Brockmann and Machleidt [15], as well as the DDHF studies for finite nuclear system in [16,17], it was shown that $g_\sigma$ and $g_\omega$ should be density dependent. Mao et al. [11] proposed a density and momentum dependence of the coupling constants of the sigma and omega field. And based on it, a trend of decrease of the cross sections at low energy as the density decreasing from normal density to $0.25\rho_0$ was shown and the cross sections at $0.25\rho_0$ was quite similar to the free cross section [11]. Therefore, the calculated free nucleon-nucleon cross sections, which are larger than experimental data at low energy range, seem to be reasonable. Since this work is mainly concentrated on the isospin dependence of the nucleon-nucleon cross section we will not involve ourselves with this aspect. We have also tested the dependence of the difference between $\sigma_{np}^{free}$ and $\sigma_{pp}^{free}$ on $g_\rho$, we find the best fit to the experimental data of $\sigma_{np}^{free}$ to $\sigma_{pp}^{free}$ can be obtained when $g_\rho$ is taken to be $-4$, which is inconsistent with [13], where the best fit to the symmetry energy is obtained based on mean field calculation.

Now let us investigate the behavior of in-medium cross sections of $\sigma_{np}^*$ and $\sigma_{pp(nn)}^*$. In addition to consider the medium correction of the nucleon mass it is also very important to take the medium correction of the $\rho$ mass into account which has already attracted a lot of studies [18–20]. Here we take the medium correction of $\rho$ mass by using the Brown-Rho scaling [18], i.e.,

$$
\frac{m_\rho^*}{m_\rho} = \frac{1}{1 + c \frac{\rho}{\rho_0}},
$$

where $c$ is a variable parameter. In this paper we simply fit it to the experimental data given in [21], that is, $m_\rho^*$ equals to 610 MeV when $\rho/\rho_0 = 0.7$, so $c$ is equal to 0.3747. With this

![Graph](image-url)

FIG. 2. The comparison of the ratio of $\sigma_{np}^{free}/\sigma_{pp(nn)}^{free}$ between the calculation results and experimental data when the contribution of $\rho$ meson field is not taken into account.

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FIG. 3. The comparison between the experimental data (left) and the calculation results (right) for $\sigma_{pp(nn)}^{free}$ and $\sigma_{np}^{free}$. 

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value, the \( \rho \) mass decreases more stiffly with increase of density than that given in [13], but the difference is not large when the density is not high. It will not change the main conclusions given in the paper. The masses of \( \sigma \) and \( \omega \) mesons are fixed since one usually considers the sigma and omega model as an effective one.

In order to investigate the respective effects from different meson fields on in-medium and free nucleon-nucleon-scattering cross sections, we show \( \sigma_{pp(nn)}^{\rho} \) and \( \sigma_{np}^{\rho} \) contributed only from \( \sigma \), \( \omega \), and \( \pi \) mesons, both \( \sigma_{pp(nn)}^{\rho} \) and \( \sigma_{np}^{\rho} \) will be monotonously suppressed at lower energy and then enhanced slightly at higher energy with the increase of the baryon density. In Figs. 4(c) and 4(d), we show \( \sigma_{pp(nn)}^{\rho} \) and \( \sigma_{np}^{\rho} \) contributed from \( \rho \) meson involved terms (including the crossing terms of \( \rho \) field with \( \sigma \), \( \omega \), and \( \pi \) field) at \( p/\rho_0 = 0, 1 \) and 2, respectively. In contrast with Figs. 4(a) and 4(b), the tendency of the contribution of \( \rho \) meson to \( \sigma_{pp(nn)}^{\rho} \) and \( \sigma_{np}^{\rho} \) is not the same as the nuclear density increasing. It is shown that the contribution from \( \rho \) meson field to \( \sigma_{np}^{\rho} \) increases with the increase of the nucleon density while the contribution of \( \rho \) meson to \( \sigma_{pp(nn)}^{\rho} \) decreases at lower energy and increases at higher energy as the density increases. To understand the reason, we further investigate the effects resulting from the medium correction of \( \rho \) meson and nucleon mass on the \( \rho \) meson contributions to \( \sigma_{pp(nn)}^{\rho} \) and \( \sigma_{np}^{\rho} \), respectively. In Figs. 4(c) and 4(d) we also show the \( \rho \) meson contributions to \( \sigma_{pp(nn)}^{\rho} \) and \( \sigma_{np}^{\rho} \) at normal density for three different cases, i.e., (a) only effective mass of nucleon taken into account, (b) only effective mass of \( \rho \) meson taken into account, and (c) effective mass of both nucleon and \( \rho \) meson taken into account are also shown (c) and (d), respectively.

![Diagram](image-url)

**FIG. 4.** The contributions of \( \sigma \), \( \omega \), and \( \pi \) to (a) \( \sigma_{pp(nn)}^{\rho} \) and (b) \( \sigma_{np}^{\rho} \) at density \( p/\rho_0 = 0, 1/3, 2/3, 1, \) and 2, respectively, as well as the contribution of \( \rho \) meson field to (c) \( \sigma_{pp(nn)}^{\rho} \) and (d) \( \sigma_{np}^{\rho} \) at density \( p/\rho_0 = 0, 1, 2 \). The contribution of \( \rho \) meson to \( \sigma_{pp(nn)}^{\rho} \) and \( \sigma_{np}^{\rho} \) at normal density for three different cases, i.e., (a) only effective mass of nucleon taken into account, (b) only effective mass of \( \rho \) meson taken into account, and (c) effective mass of both nucleon and \( \rho \) meson taken into account are also shown (c) and (d), respectively.
dependence of $\sigma_{np}^*$ as can be seen in Figs. 5(a) and 5(b). Here we show the in-medium cross sections $\sigma_{np}^*$ and $\sigma_{pp(nn)}^*$ at one and 2 times normal density, respectively, in which all of the contributions of $\sigma$, $\omega$, $\pi$, and $\rho$ mesons and the medium corrections of both nucleon and $\rho$ mass are included.

IV. SUMMARY AND OUTLOOK

In this paper, we first study the marked different behavior of $\sigma_{np}^{\text{free}}$ and $\sigma_{np}^{\text{free}}$ when different sets of coupling constants are adopted, it seems that if $g_\omega > g_\pi$ and $g_\omega - g_\pi < -2$ we can approximately reproduce the tendency of the energy dependence of $\sigma_{pp(nn)}^{\text{free}}$ and $\sigma_{np}^{\text{free}}$. Then we study the isospin dependence of the nucleon-nucleon scattering cross section and we find if only considering the contributions of $\sigma$ and $\omega$ fields, we cannot reproduce the difference of $\sigma_{pp(nn)}^{\text{free}}$ and $\sigma_{np}^{\text{free}}$ at lower energy which is found in experimental data. Our results indicate that $\rho$ meson field plays a dominant role in the isospin dependence of the nucleon-nucleon elastic cross sections, while $\pi$ meson field plays a negligible role. By taking the contribution of $\rho$ meson field into account, the isospin dependence of the nucleon-nucleon elastic cross sections can be reproduced reasonably well. For the medium effects, in addition to the medium correction of the nucleon mass, we stress on the effects of the medium correction of the $\rho$ mass. Our results have demonstrated the different behaviors of the effects resulting from the medium correction of $\rho$ mass and nucleon mass on $\sigma_{pp(nn)}^{\text{free}}$ and $\sigma_{np}^{\text{free}}$, respectively, which leads to enhance $\sigma_{np}^*$ and suppress $\sigma_{pp(nn)}^*$ at lower energy and enhance it at higher energy with the increase of the density. So, for $\sigma_{pp(nn)}^*$, the medium effects from the contributions of the $\sigma$ and $\omega$ meson terms are at the same direction with that of $\rho$ meson term, the total effects consequently result in a strong density dependence in $\sigma_{pp(nn)}^*$. While, for $\sigma_{np}^*$, the medium effects on the contributions of $\sigma$ and $\omega$ mesons and that of $\rho$ mesons to $\sigma_{np}^*$ are of opposite, this cancellation makes the density dependence of $\sigma_{np}^*$ very weak. Thus, a commonly adopted phenomenological expression for in-medium nucleon-nucleon elastic cross section $\sigma^* = [1 - \alpha(\rho/\rho_0)] \sigma^{\text{free}}$ should make some change concerning the different behavior of medium corrections of $\sigma_{np}^*$ and $\sigma_{pp(nn)}^*$. In order to take the isospin dependence of the medium correction into account, an isospin dependent $\alpha$ should be introduced in the phenomenological expression when applying it to the transport theory approach for heavy ion collisions at low and intermediate energy.

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