In-medium $NN \to N\Delta$ cross sections from constrained relativistic mean field models*

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Abstract: The theoretical prediction on the the in-medium $NN \to N\Delta$ cross sections based on a one boson exchange model involves significant parameter uncertainties. In this work, we reduce these uncertainties by employing relativistic mean field (RMF) models constrained by neutron star observations. Specifically, the range of the correction factors $R = \sigma^*_{NN\to N\Delta}/\sigma^{free}_{NN\to N\Delta}$ is significantly narrowed at nuclear densities above saturation.

Keywords: in-medium NN → NΔ cross sections, isospin-asymmetric nuclear matter, relativistic mean field models, equation of state

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The medium NN cross sections in transport mode simulations play a crucial role in intermediate-energy heavy ion collisions (HIC), as they significantly influence the predictions of reaction dynamics, collective flow, stopping power, and particle productions [1−9]. In the transport model simulations, the in-medium $NN \to N\Delta$ cross sections are a critical component of the $\pi - N - \Delta$ loops, which can effect the pion multiplicity data. The π^-/π^+ ratio serves as a sensitive observable for probing the symmetry energy at suprasaturation density. For reproducing the pion multiplicity data, the in-medium $NN \to N\Delta$ cross section ($\sigma^*_{NN\to N\Delta}$) is one of the important ingredients because it will directly influence the first Δ production which can decay into nucleon and pion or rescatter with nucleons.

Many transport codes adopted the free space $NN \to N\Delta$ cross section, i.e., the $\sigma^{\rm free}_{NN\to N\Delta}$ taken from Ref. [10], or phenomenological in-medium cross section, i.e., $\sigma^*_{NN\to N\Delta} = R\sigma^{\rm free}_{NN\to N\Delta}$, in the collision integral of transport models [11]. Recent transport model comparison studies by the transport model evaluation project (TMEP) collaboration highlight the large model dependence in pion yields and the need for improved in-medium inputs [12−18]. The isospin independent microscopic approaches have been employed to investigate the in-medium $NN \to N\Delta$ cross sections in symmetric nuclear matter [19−25], where the medium correction factor R is the same for for all channels of the $NN \to N\Delta$ process. For the isospin asymmetric nuclear matter, Li el at. studied the in-medium $NN \to N\Delta$ cross section without considering the mass distribution of Δ resonance and threshold effects by using the relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) microscopic transport theory based on the closed time-path Green's function technique in Ref. [26].

In our previous work [27], the in-medium $NN \to N\Delta$ cross section $\sigma^*_{NN\to N\Delta}$ by considering the threshold effect and the mass distribution of the Δ resonance in asymmetric nuclear matter. Further, the dependence of medium correction factor R on the relativistic mean field parameters was investigated in our previous work [28]. With 3 RMF models, i.e., NL$\rho\delta$ [29], DDMEδ [30], DDRH$\rho\delta$ [31], our results show that R increases with the slope parameter L when using δ parameter sets for a given isospin asymmetry. To better understand the influence of the δ meson on the in-medium $NN \to N\Delta$ cross sections, we compared calculations of R performed with and without δ-meson parameter sets in our subsequent work [32]. The results indicate that, when using parameter sets without the δ meson, the cross-section factors satisfy $R_{pp\to n\Delta^{++}} < R_{nn\to p\Delta^-}$ and $R_{NN\to N\Delta^+} < R_{NN\to N\Delta^0}$, while the opposite trend is observed when the δ meson meson is included.

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However, with more than 300 available mean field models, there exists large uncertainty in these cross section results. Therefore, it is essential to reduce the in-medium $NN \to N\Delta$ cross sections, especially because they are increasingly vital for improving transport models — particularly in the context of pion production and for further constraining the symmetry energy at suprasaturation densities. In this paper, we provide reductions on the range of values for the in-medium $NN \to N\Delta$ cross sections in isospin asymmetric nuclear matter, based on a selected subset of RMF models that have been constrained by neutron star observations, as discussed in our previous work [33].

The paper is organized as follows. First, we briefly describe the properties of nuclear matter for different RMF models. Next, we discuss the constraints on the in-medium correction factor R for $NN \to N\Delta$ cross sections. Finally, we provide a summary of our findings.

For the calculation of the in-medium $NN \to N\Delta$cross section in nuclear matter, we employ a one-boson exchange model based on a relativistic Lagrangian that includes both nucleons and Δ. According to the structure of the Lagrangian, three types of RMF parameter sets are adopted to estimate the in-medium cross section, as discussed in Ref. [34]: (i) nonlinear models, (ii) density-dependent models, and (iii) point-coupling models. Detailed descriptions of these RMF models are provided in Appendix A. Subsequently, the in-medium $NN \to N\Delta$ cross sections are calculated based on the respective RMF Lagrangians, and the detailed derivation of the cross sections can be found in Appendix B.

We employ the same RMF Lagrangian to derive the nuclear matter properties, as detailed in Appendix A. Here, the binding energy per particle in asymmetric nuclear matter is expressed as follows:

$$E(\rho,\alpha) = \frac{\epsilon}{\rho} - m_N = E_0(\rho) + S(\rho)\alpha^2 + O(\alpha^4), \tag{1}$$

where the $E_0(\rho) = E(\rho, \alpha = 0)$ is the binding energy in symmetric nuclear matter and $S(\rho)$ denotes the symmetry energy. Here, $\rho = \rho_n + \rho_p$ represents the total nuclear matter density, ϵ is the energy density, m_N is the nucleon mass, and $\alpha = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry. The nuclear symmetry energy $S(\rho)$ is defined as

$$S(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\alpha)}{\partial\alpha^2}\Big|_{\alpha=0}. \tag{2}$$

The symmetry energy is expanded in terms of $(\rho-\rho_0)/3\rho_0$:

$$S(\rho) = J + \frac{L}{3\rho_0}(\rho-\rho_0) + \frac{K_{sym}}{2}\frac{(\rho-\rho_0)^2}{\rho_0^2} + \cdots. \tag{3}$$

Here, $J = S(\rho_0)$ represents the symmetry energy at saturation density ρ_0. The parameters $L = 3\rho_0\frac{\partial S}{\partial\rho}|_{\rho=\rho_0}$ and $K_{sym} = 9\rho_0^2\frac{\partial^2 S}{\partial\rho^2}|_{\rho=\rho_0}$ denote the slope and curvature of the symmetry energy at saturation density, respectively.

The coupling constants in RMF models are crucial for predicting the in-medium Δ production cross section as well as for determining the equation of state (EOS) of nuclear matter. To reduce the uncertainty in the in-medium $NN \to N\Delta$ cross sections, it is essential to select reasonable RMF models. In previous work [33], the EOS of nuclear matter was constrained using neutron star observations based on various RMF parameter sets. In this study, we calculate the in-medium $NN \to N\Delta$ cross sections using 180 RMF interaction sets, as described in Refs. [33, 35].

Furthermore, an important task is to further evaluate the in-medium $NN \to N\Delta$ cross sections using the selected RMF parameter sets that have been refined based on multiple neutron star observables from Refs. [33, 36, 37]. The final constrained RMF models are: HC, FSUGZ03, IU-FSU, G2*, BSR8, BSR9, FA3, FZ3, and DD-F. The EOS parameters (incompressibility K_0, symmetry energy J, slope of symmetry energy L, and curvature of symmetry K_{sym}) used in this work from with and without NS observations are both listed in Table 1. Additionally, the properties of nuclear matter and related parameters of all RMF models used here are detailed in Table C1 of Appendix C.

As a key step in calculating the in-medium cross sections (see Eq. 48 in Appendix B), it is first necessary to determine the Dirac effective masses of nucleons, the effective pole masses of Δ resonances, and the channel-dependent changes in vector self-energies. These quantities must be obtained based on the RMF parameter sets that have been constrained as described earlier.

In the Fig. 1, we plot the effective mass of the nucleon (m_N^*/m_N) and effective pole masses of Δ ($m_{0,\Delta}^*/m_{0,\Delta}$) as function of ρ/ρ_0 in symmetric nuclear matter. Except for NL$\rho\delta$A [29], NL$\rho\delta$B [29], DDMEδ [30] and DDRH$\rho\delta$ [31], all others included the constraint RMF models are without-δ models. Consequently, these models do not exhibit mass splitting between protons and neutrons (or

Table 1. Ranges of the EOS from the used RMF models.

	K_0(MeV)	J (MeV)	L(MeV)	K_{sym}(MeV)
With neutron star constraint	216.87–297.75	29.70–31.62	29.08–69.86	-275.05–28.99
Without neutron star constraint	199.92–300.67	17.37–43.54	29.08–140.37	-275.05–398.27

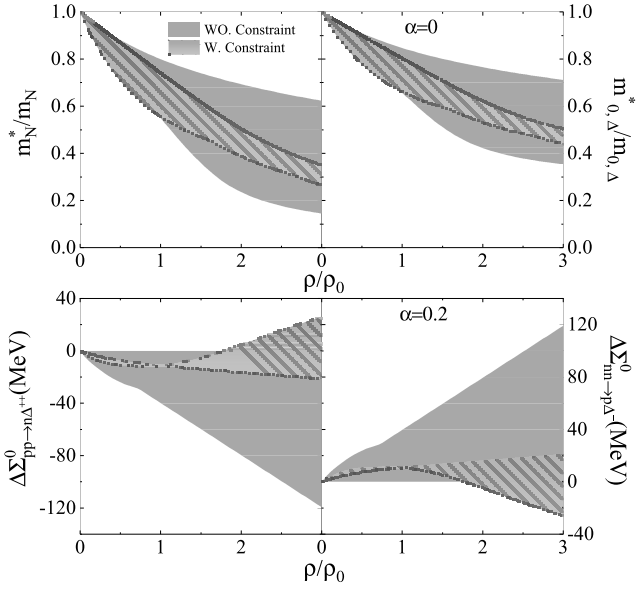

Fig. 1. (Color online) The upper panels show the effective mass of the nucleon (m_N^*/m_N) and effective pole masses of Δ ($m_{0,\Delta}^*/m_{0,\Delta}$) in symmetric nuclear matter as functions of ρ/ρ_0. The lower panels display the changes in vector self-energies $\Delta\Sigma^0 pp \to n\Delta^{++}$ and $\Delta\Sigma^0 nn \to p\Delta^-$ in asymmetric nuclear matter with $\alpha = 0.2$. The pure gray areas represent the ranges of all considered RMF models, and the hatched areas indicate the subset constrained by neutron star observations. The constrained shaded band denotes the model-ensemble envelope—range from minimal to maximal values across all RMF interactions that pass the neutron-star filters—and is not a statistical confidence interval.

among different Δ isospin states). Therefore, we only show the effective masses in symmetric nuclear matter.

Because the most RMF models are adjusted to describe the nuclei and nuclear matter in the density region from near subsaturation density $\rho \approx 2/3\rho_0$(which represents the average value between the central and surface densities [38−43]) up to saturation density, significant uncertainties remain regarding RMF model properties — such as effective masses—at densities above ρ_0.

From the results in Fig. 1, we can see that the uncertainty of the effective masses reduced, i.e., the range of $\Delta m_N^* = \frac{m_{N,max}^* - m_{N,min}^*}{m_N} = 0.196$ (corresponding to $m_N^*/m_N = 0.551 - 0.747$) at ρ_0, while $m_N^*/m_N = 0.677$–0.709 (corresponding to Δm_N^*=0.032) are deduced at 68% confidence level from just three types of momentum dependence of the optical potential model in Ref. [44]. Additionally, the range of $\Delta m_{0,\Delta}^*$ are also decreased, especially at the density above saturation density.

From our previous work [32], we observed that there remains a splitting among different channels of the in-medium $NN \to N\Delta$ cross sections in asymmetric nuclear matter. To illustrate this effect, we present the vector self-energy changes for two representative channels in asymmetric matter at $\alpha = 0.2$:

$$\Delta\Sigma^0_{pp\to n\Delta^{++}} = \Sigma^0_p + \Sigma^0_p - \Sigma^0_n - \Sigma^0_{\Delta^{++}},$$

and

$$\Delta\Sigma^0_{nn\to p\Delta^-} = \Sigma^0_n + \Sigma^0_n - \Sigma^0_p - \Sigma^0_{\Delta^-}.$$

These channels, $pp \to n\Delta^{++}$ and $nn \to p\Delta^-$, are highlighted because they are the main contributors to the $NN \to N\Delta$ processes.

The results indicate that the uncertainties in both the effective masses and the vector self-energy changes are significantly reduced when using the constrained RMF models, especially at higher densities. Consequently, the uncertainties in the in-medium $NN \to N\Delta$ cross sections are expected to be correspondingly diminished.

Fig. 2 displays the in-medium $pp \to n\Delta^{++}$ cross sections as a function of the total energy $\sqrt{s}$ in symmetric nuclear matter. The left panel compares the cross sections in free space and at saturation density, while the middle and right panels present the cross sections $\sigma^*_{pp\to n\Delta^{++}}$ at $\rho = 2\rho_0$ and $3\rho_0$, respectively. Compared with the unconstrained results, the constrained in-medium cross sections show a notably reduced spread, particularly at densities above ρ_0. This reduction in uncertainty of in-medium cross section is consistent with the behaviors of the nucleon and Δ effective masses shown in Fig. 1. The in-medium $NN \to N\Delta$ cross section depends explicitly on the effective masses (m_N^* and $m_{0,\Delta}^*$) in symmetric nuclear matter (the channel-dependent vector self-energy changes $\Delta\Sigma^0$ should be also considered in asymmetric nuclear matter), which can be derived from Appendix B. Bulk "nuclear-matter properties" such as K_0, J, L and K_{sym} do not enter the cross-section formula directly, which are determined by RMF interactions. After applying neutron-star constraints, the surviving RMF sets develop similar trajectories of $m^*(\rho)$ and $\Delta\Sigma^0(\rho)$ at 2 to $3\rho_0$, which lead to the observed narrowing of in-medium cross sections, even though the spread in incompressibility of the same sets may remain sizable (e.g. FA3 and FZ3).

Since there is no isospin splitting of effective masses in symmetric nuclear matter, the in-medium cross section for $nn \to p\Delta^-$ is identical to that for $pp \to n\Delta^{++}$. Cross sections for other channels can be obtained by applying the appropriate isospin Clebsch-Gordan coefficients, yielding values equal to $\frac{1}{3}\sigma^*_{pp\to n\Delta^{++}}$. Consequently, the ratio $R = \sigma^*_{NN\to N\Delta}/\sigma_{NN\to N\Delta}$ is the same for all channels of $NN \to N\Delta$ in symmetric nuclear matter.

Fig. 3 shows the medium correction factors R (top panels) and the corresponding range $\Delta R = R_{\max} - R_{\min}$ (bottom panels) as a function of ρ/ρ_0 for beam energies

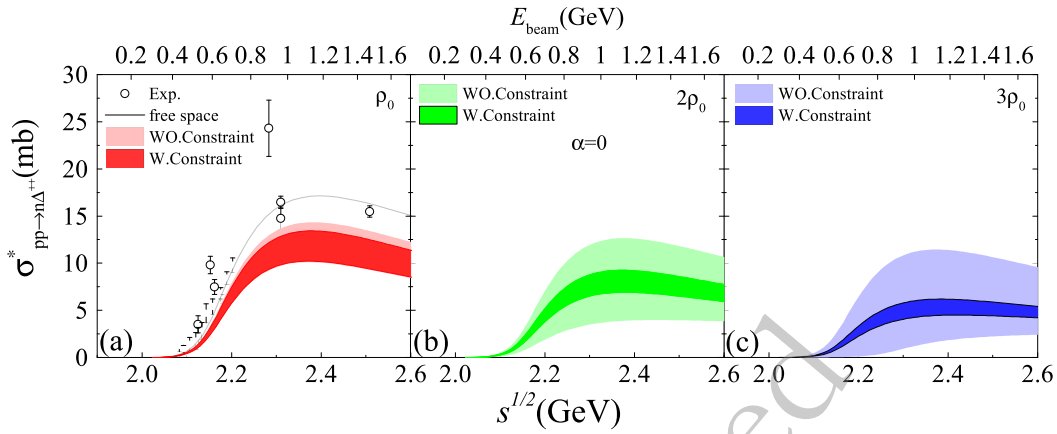

Fig. 2. (Color online) The in-medium $pp \to n\Delta^{++}$ cross section as function of $\sqrt{s}$ in symmetric nuclear matter. The left panel shows the cross section in free space and at ρ_0, while the middle and right panels present results at $2\rho_0$ and $3\rho_0$, respectively. The experimental data are taken from Ref. [45].

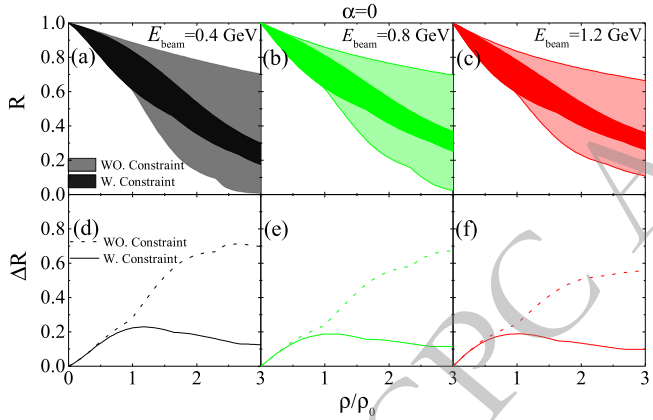

Fig. 3. (Color online) The upper panels are R as a function of density ρ/ρ_0 at beam energy $E_{beam} = 0.4$, 0.8, and 1.2 GeV in symmetric nuclear matter. The lower panels display the corresponding range ΔR.

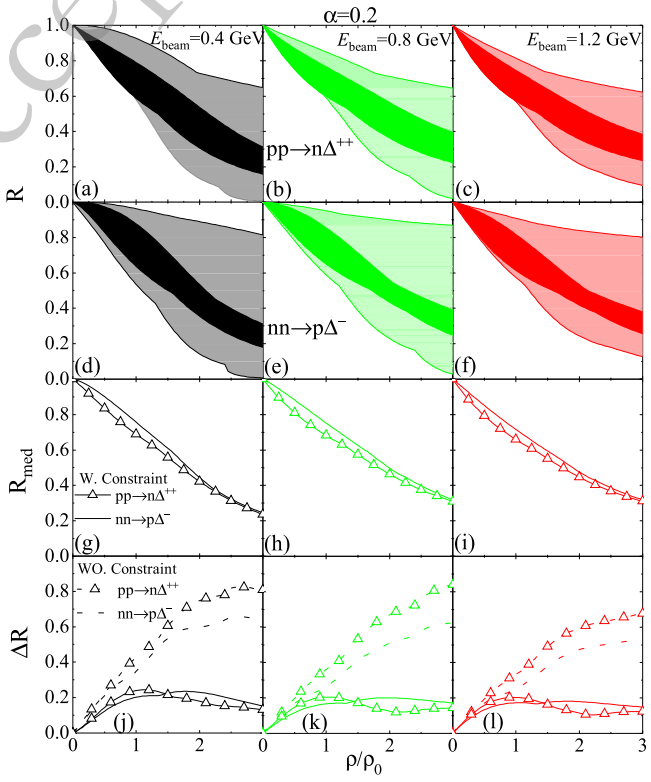

Fig. 4. (Color online) The in-medium correction factor R for $pp \to n\Delta^{++}$ (a, b, c panels) and $nn \to p\Delta^-$ (d,e,f panels), the constraint median values of correction factors R_{med} (g, h, i panels), and ΔR (j, k, l panels) as function of density ρ/ρ_0 in asymmetric nuclear matter with $\alpha = 0.2$.

$E_{\rm beam} = 0.4, 0.8$, and 1.2 GeV in symmetric nuclear matter. The unconstrained ΔR increases with density, but once constraints are applied to the in-medium cross sections, the spread in R is notably reduced compared to the unconstrained results. For instance, at $E_{\rm beam} = 0.4$ GeV, ΔR decreases from 0.283 to 0.219 at ρ_0, from 0.648 to 0.182 at $2\rho_0$, and from 0.696 to 0.125 at $3\rho_0$. This reduction stems from the decreased uncertainty in effective masses (see Fig. 1).

Here we take the $pp \to n\Delta^{++}$ and $nn \to p\Delta^-$ channels as examples to illustrate the in-medium cross sections in asymmetric nuclear matter. In Fig. 4, we plot R for $pp \to n\Delta^{++}$ (panels (a), (b), (c)) and $nn \to p\Delta^-$ (panels (d), (e), (f)), the constrained median values $R_{\rm med}$ (panels (g), (h), (i)), and the range ΔR (panels (j), (k), (l)) as functions of ρ/ρ_0 in asymmetric nuclear matter with $\alpha = 0.2$ for $E_{\rm beam} = 0.4$, 0.8, and 1.2 GeV.

It is also evident that the constrained median values of the in-medium $NN \to N\Delta$ cross sections follow $R_{pp\to n\Delta^{++}} < R_{nn\to p\Delta^-}$, consistent with Ref. [32].

Furthermore, the constrained correction factors R in asymmetric nuclear matter are notably smaller than their unconstrained counterparts. For instance, at ρ_0, $\Delta R_{pp\to n\Delta^{++}}$ decreases from 0.347 to 0.202, while $\Delta R_{nn\to p\Delta^-}$ decreases from 0.427 to 0.238. Similar reductions are observed at

$2\rho_0$ and $3\rho_0$. For example, at $2\rho_0$, $\Delta R_{pp\to n\Delta^{++}}$ decreases from 0.593 to 0.230, whereas $\Delta R_{nn\to p\Delta^-}$ decreases from 0.746 to 0.178. Overall, the restricted ΔR decreases by about 42%–44%, 61%–76%, and 76%–84% from $pp \to n\Delta^{++}$ to $nn \to p\Delta^-$ at at ρ_0, $2\rho_0$ and $3\rho_0$ respectively for $E_{beam} = 0.4$ GeV, as well as for other beam energies.

Evaluating the in-medium $NN \to N\Delta$ cross sections in asymmetric nuclear matter is crucial for heavy-ion collision studies, as it provides a potential avenue for reducing uncertainties in the symmetry energy at suprasaturation densities. To facilitate their application in transport models, we present parameterizations of the constrained in-medium cross section correction factors R for all $NN \to N\Delta$ channels at beam energies $E_{\rm beam} = 0.4, 0.6, 0.8, 1.0,$ and 1.2 GeV, both in symmetric and asymmetric nuclear matter.

In summary, we present the evaluated the in-medium $NN \to N\Delta$ cross sections derived from RMF parameter sets constrained by neutron star observations [33]. Compared to the unconstrained results, our findings show that the ranges of $\sigma^*_{NN\to N\Delta}$ are significantly reduced over the density range $0 < \rho \le 3\rho_0$ for beam energies of $E_{\rm beam} = 0.4, 0.8,$ and 1.2 GeV in both symmetric and asymmetric nuclear matter, especially at densities above ρ_0. For completeness, the parameterized forms of the in-medium $NN \to N\Delta$ cross-section corrections are given in the supplemental material.

We hope the constrained in-medium cross sections will help reduce the uncertainties of information on the symmetry energy at high densities by facilitating them in the prediction of pion observables in QMD models to simulate heavy-ion collision experiments, such as those performed by the HADES (Au+Au) [46] and MSU (Sn+Sn) [15]. However, matter created in heavy ion collisions is hot and in a non-equilibrium state, implying that the in-medium $NN \to N\Delta$ cross section depends on temperature. Prior work has explored the temperature dependence of in-medium nucleon-nucleon scattering cross sections (see Ref. [47]), reporting a possible enhancement at finite temperature relative to the cold matter case. The explicit temperature dependence of in-medium $NN \to N\Delta$ cross sections is rarely discussed, and we will investigate it in future work.

APPENDIX A: RELATIVISTIC MEAN FIELD

In this paper, we ignore the Fock term in the relativistic mean field, where models are all Hartree RMF model sets.

1. Nonlinear relativistic mean field

The Lagrangians are nonlinear RMF model are:

$$\mathcal{L}_{NL} = \mathcal{L}_F + \mathcal{L}_I, \tag{A1}$$

where $\mathcal{L}_F$ is,

$$\begin{aligned}\mathcal{L}_F =& \bar{\Psi}[i\gamma_\mu\partial^\mu - m_N]\Psi + \bar{\Delta}_\lambda[i\gamma_\mu\partial^\mu - m_\Delta]\Delta^\lambda \\ &+ \frac{1}{2}\left(\partial_\mu\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi} - m_\pi^2\boldsymbol{\pi}^2\right) + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - U(\sigma) \\ &- \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}\zeta^4(\omega_\mu\omega^\mu)^2 \\ &- \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu + \frac{1}{2}\left(\partial_\mu\boldsymbol{\delta}\partial^\mu\boldsymbol{\delta} - m_\delta^2\boldsymbol{\delta}^2\right) \\ &+ g_\sigma g_\omega^2\sigma\omega_\mu\omega^\mu(\alpha_1 + \frac{1}{2}\alpha_1' g_\sigma) + g_\sigma g_\rho^2\sigma\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu(\alpha_2 + \frac{1}{2}\alpha_2' g_\sigma) \\ &+ \frac{1}{2}\alpha_3' g_\omega^2 g_\rho^2\omega_\mu\omega^\mu\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu\,.\end{aligned} \tag{A2}$$

and $\mathcal{L}_I$ is interaction part,

$$\begin{aligned}\mathcal{L}_I =& g_{\sigma NN}\bar{\Psi}\Psi\sigma - g_{\omega NN}\bar{\Psi}\gamma_\mu\Psi\omega^\mu - g_{\rho NN}\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\cdot\Psi\boldsymbol{\rho}^\mu \\ &- \frac{f_{\pi NN}}{m_\pi}\bar{\Psi}\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\Psi\partial^\mu\boldsymbol{\pi} + g_{\delta NN}\bar{\Psi}\boldsymbol{\tau}\cdot\Psi\boldsymbol{\delta} \\ &+ g_{\sigma\Delta\Delta}\bar{\Delta}_\mu\Delta^\mu\sigma - g_{\omega\Delta\Delta}\bar{\Delta}_\mu\gamma_\nu\Delta^\mu\omega^\nu \\ &- g_{\rho\Delta\Delta}\bar{\Delta}_\mu\gamma_\nu\mathbf{T}\cdot\Delta^\mu\boldsymbol{\rho}^\nu + \frac{g_{\pi\Delta\Delta}}{m_\pi}\bar{\Delta}_\mu\gamma_\nu\gamma_5\mathbf{T}\cdot\Delta^\mu\partial^\nu\boldsymbol{\pi} \\ &+ g_{\delta\Delta\Delta}\bar{\Delta}_\mu\mathbf{T}\cdot\Delta^\mu\boldsymbol{\delta} + \frac{g_{\pi N\Delta}}{m_\pi}\bar{\Delta}_\mu\mathcal{T}\cdot\Psi\partial^\mu\boldsymbol{\pi} \\ &+ \frac{ig_{\rho N\Delta}}{m_\rho}\bar{\Delta}_\mu\gamma_\nu\gamma_5\mathcal{T}\cdot\Psi(\partial^\nu\boldsymbol{\rho}^\mu - \partial^\mu\boldsymbol{\rho}^\nu) + h.c.\end{aligned} \tag{A3}$$

In Eq. (A2), $\omega_{\mu\nu}$ and $\boldsymbol{\rho}_{\mu\nu}$ are defined as $\partial_\mu\omega_\nu - \partial_\nu\omega_\mu$ and $\partial_\mu\boldsymbol{\rho}_\nu - \partial_\nu\boldsymbol{\rho}_\mu$, respectively. The nonlinear potential of the σ field is given by $U(\sigma) = \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4$. Here $\boldsymbol{\tau}$ and $\mathbf{T}$ are the isospin matrices for the nucleon and Δ [48, 49], while $\mathcal{T}$ is the isospin transition matrix between the isospin 1/2 and the 3/2 fields [10].

In the uniform rest nuclear matter, the effective momentum can be written as $\mathbf{p}_i^* = \mathbf{p}_i$ since the spatial components of vector field vanish, i.e., $\boldsymbol{\Sigma} = 0$. Thus, in the mean field approach, the effective energy is given by:

$$p_i^{*0} = p_i^0 - \Sigma_i^0, \tag{A4}$$

The effective masses of nucleon and Δ read as:

$$m_i^* = m_i + \Sigma_i^S, \tag{A5}$$

Here Σ_i^0 and Σ_i^S represent the vector and scalar self-energy respectively for the RMF parameter sets.

The vector and scalar potentials in the nonlinear(NL) RMF model are expressed as:

$$\Sigma^0_{i,NL} = g_\omega \bar{\omega}^0 + g_\rho t_{3,i} \bar{\rho}^0_3 \tag{A6}$$

$$\Sigma^S_{i,NL} = -g_\sigma \bar{\sigma} - g_\delta t_{3,i} \bar{\delta}_3 \tag{A7}$$

where $t_{3,i}$ represents the third component of the isospin of the nucleon and Δ, with the following values: $t_{3,n} = -1$, $t_{3,p} = 1$, $t_{3,\Delta^{++}} = 1$, $t_{3,\Delta^{+}} = \frac{1}{3}$, $t_{3,\Delta^{0}} = -\frac{1}{3}$, $t_{3,\Delta^{-}} = -1$. The $\bar{\omega}^0$, $\bar{\rho}^0_3$, $\bar{\sigma}$ and $\bar{\delta}_3$ denote the expectation values of the mesons field in the mean-field approximation. In the RMF model, the equations of motion for the mesons are:

$$\begin{aligned} m^2\bar{\sigma} = {} & g_\sigma \rho_s - g_2\bar{\sigma}^2 - g_3\bar{\sigma}^3 + g_\sigma g_\omega^2 (\bar{\omega}^0)^2(\alpha_1 + \alpha'_1 g_\sigma \bar{\sigma}) \\ & + g_\sigma g_\rho^2 (\bar{\rho}^0_3)^2(\alpha_2 + \alpha'_2 g_\sigma \bar{\sigma}) \end{aligned} \tag{A8}$$

$$\begin{aligned} m^2_\omega \bar{\omega}^0 = {} & g_\omega \rho - \zeta g^4_\omega (\bar{\omega}^0)^3 - g_\sigma g^2_\omega \bar{\sigma}\bar{\omega}^0(2\alpha_1 + \alpha'_1 g_\sigma \bar{\sigma}) \\ & - \alpha'_3 g^2_\omega g^2_\rho (\bar{\rho}^0_3)^2 \bar{\omega}^0 \end{aligned} \tag{A9}$$

$$\begin{aligned} m^2_\rho \bar{\rho}^0_3 = {} & g_\rho \rho_3 - g_\sigma g^2_\rho \bar{\sigma}\bar{\rho}^0_3(2\alpha_2 + \alpha'_2 g_\sigma \bar{\sigma}) \\ & - \alpha'_3 g^2_\omega g^2_\rho \bar{\rho}^0_3 (\bar{\omega}^0)^2 \end{aligned} \tag{A10}$$

$$m^2_\delta \bar{\delta}_3 = g_\delta \rho_{s3} \tag{A11}$$

The nucleon densities are (assuming no Δ density):

$$\rho_s = \langle \bar{\Psi}\Psi \rangle = \rho_{sn} + \rho_{sp} \tag{A12}$$

$$\rho = \langle \bar{\Psi}\gamma^0\Psi \rangle = \rho_n + \rho_p \tag{A13}$$

$$\rho_{s3} = \langle \bar{\Psi}\tau_3\Psi \rangle = \rho_{sp} - \rho_{sn} \tag{A14}$$

$$\rho_3 = \langle \bar{\Psi}\gamma^0\tau_3\Psi \rangle = \rho_p - \rho_n \tag{A15}$$

With Fermi momenta $k_{F,i}$ for i = n or p, the scalar and vector densities are:

$$\begin{aligned} \rho_{si} &= \frac{C(i)}{(2\pi)^3}\int_{k<k_{Fi}} d^3\mathbf{k} \frac{m^*_i}{\sqrt{k^2 + m^{*2}_i}} \\ &= \frac{m^*_i}{2\pi^2}\left[k_{Fi}E^*_{Fi} - m^{*2}_i \ln\frac{k_{Fi} + E^*_{Fi}}{m^*_i}\right] \end{aligned} \tag{A16}$$

$$\rho_i = \frac{C(i)}{(2\pi)^3}\int_{k<k_{Fi}} d^3\mathbf{k} = \frac{k^3_{Fi}}{3\pi^2} \tag{A17}$$

where the degeneracy factor $C(i = n, p) = 2$, and $E^*_{Fi} = \sqrt{k^2_{Fi} + m^{i*}}$ is the Fermi energy of neutrons and protons.

The eigenvalues of neutron and proton from the Dirac equation are:

$$e_n = g_\omega \bar{\omega}^0 - g_\rho \bar{\rho}^0_3 + \sqrt{k^{2*}_n + m^{*2}_n}, \tag{A18}$$

$$e_p = g_\omega \bar{\omega}^0 + g_\rho \bar{\rho}^0_3 + \sqrt{k^{2*}_p + m^{*2}_p}. \tag{A19}$$

The expression for the energy density and pressure are obtained from the given Lagrangian using energy momentum tensor relation given by,

$$T^{\mu\nu} = \sum_i \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}\partial^\nu \phi_i - g^{\mu\nu}\mathcal{L}, \tag{A20}$$

where ϕ_i runs over all possible fields. The energy density ϵ and pressure P can be obtain from the energy-momentum tensor:

$$\begin{aligned} \epsilon_{NL} = \langle T^{00} \rangle = {} & \frac{1}{2}m^2_\sigma\bar{\sigma}^2 + \frac{1}{3}g_2\bar{\sigma}^3 + \frac{1}{4}g_3\bar{\sigma}^4 - \frac{1}{2}m^2_\omega(\bar{\omega}^0)^2 \\ & - \frac{\zeta}{4}g^4_\omega(\bar{\omega}^0)^4 + g_\omega\bar{\omega}^0\rho - \frac{1}{2}m^2_\rho(\bar{\rho}^0_3)^2 + g_\rho\bar{\rho}^0_3\rho_3 \\ & + \frac{1}{2}m^2_\delta\bar{\delta}^2_3 - g_\sigma g^2_\omega\bar{\sigma}(\bar{\omega}^0)^2(\alpha_1 + \frac{1}{2}\alpha'_1 g_\sigma\bar{\sigma}) \\ & - g_\sigma g^2_\rho\bar{\sigma}(\bar{\rho}^0_3)^2(\alpha_2 + \frac{1}{2}\alpha'_2 g_\sigma\bar{\sigma}) - \frac{1}{2}\alpha'_3 g^2_\omega g^2_\rho(\bar{\rho}^0_3)^2(\bar{\omega}^0)^2 \\ & + \frac{1}{4}[3E^*_{Fn}\rho_n + m^*_n\rho_{sn}] + \frac{1}{4}[3E^*_{Fp}\rho_p + m^*_p\rho_{sp}], \end{aligned} \tag{A21}$$

and

$$\begin{aligned} P_{NL} = {} & \frac{1}{3}\sum_{i=1}^{3}\langle T^{ii} \rangle = -\frac{1}{2}m^2_\sigma\bar{\sigma}^2 - \frac{1}{3}g_2\bar{\sigma}^3 - \frac{1}{4}g_3\bar{\sigma}^4 \\ & + \frac{1}{2}m^2_\omega(\bar{\omega}^0)^2 + \frac{\zeta}{4}g^4_\omega(\bar{\omega}^0)^4 + \frac{1}{2}m^2_\rho(\bar{\rho}^0_3)^2 \\ & - \frac{1}{2}m^2_\delta\bar{\delta}^2_3 + g_\sigma g^2_\omega\bar{\sigma}(\bar{\omega}^0)^2(\alpha_1 + \frac{1}{2}\alpha'_1 g_\sigma\bar{\sigma}) \\ & + g_\sigma g^2_\rho\bar{\sigma}(\bar{\rho}^0_3)^2(\alpha_2 + \frac{1}{2}\alpha'_2 g_\sigma\bar{\sigma}) + \frac{1}{2}\alpha'_3 g^2_\omega g^2_\rho(\bar{\rho}^0_3)^2(\bar{\omega}^0)^2 \\ & + \frac{1}{4}[E^*_{Fn}\rho_n - m^*_n\rho_{sn}] + \frac{1}{4}[E^*_{Fp}\rho_p - m^*_p\rho_{sp}]. \end{aligned} \tag{A22}$$

The same calculations for density-dependence and point-coupling models can be found in Refs.[30, 31, 50−52].

For symmetric nuclear matter, $m^*_n = m^*_p = m^*_N$ since $\bar{\delta}_3$ vanishes.

The expressions of the symmetry energy and slope of symmetry energy L for nonlinear RMF models are:

$$S(\rho)_{NL} = \frac{k_F^2}{6E_F^*} + \frac{1}{2}\rho\frac{g_\rho^2}{m_\rho^{*2}} - \frac{1}{2}\rho\left(\frac{\frac{g_\delta^2}{m_\delta^2}m_N^{*2}}{E_F^{*2}\left[1+\frac{g_\delta^2}{m_\delta^2}A(\rho,m_N^*)\right]}\right), \tag{A23}$$

where $m_\rho^{*2} = m_\rho^2 + g_\sigma g_\rho^2\bar{\sigma}(2\alpha_2 + \alpha_2' g_\sigma\bar{\sigma}) + \alpha_3' g_\omega^2 g_\rho^2(\bar{\omega}^0)^2$, and

$$A(\rho,m_N^*) = 3\left(\frac{\rho_s}{m_N^*} - \frac{\rho}{E_F^*}\right). \tag{A24}$$

$$\begin{aligned} L_{NL} = {} & \frac{k_F^2}{3E_F^*}\left(1-\frac{k_F^2}{2E_F^{*2}} - \frac{k_F^3 m_N^*}{E_F^{*2}\pi^2}\frac{\partial m_N^*}{\partial\rho}\right) \\ & + \frac{3g_\rho^2}{2m_\rho^{*2}}\rho\left(1-\frac{1}{m_\rho^{*2}}\frac{\partial m_\rho^{*2}}{\partial\rho}\rho\right) \\ & - \frac{1}{2}\rho\left(\frac{\frac{g_\delta^2}{m_\delta^2}m_N^{*2}}{E_F^{*2}\left[1+\frac{g_\delta^2}{m_\delta^2}A(\rho,m_N^*)\right]}\right) \\ & \times\left\{3-\frac{2k_F^2}{E_F^{*2}} + 6\left(1-\frac{m_N^{*2}}{E_F^{*2}}\right)\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right. \\ & - 3\frac{g_\delta^2}{m_\delta^2}\frac{1}{1+\frac{g_\delta^2}{m_\delta^2}A}\left[2A\left(\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right)\right. \\ & \left.\left. + \rho\frac{k_F^2}{E_F^{*3}}\left(1-3\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right)\right]\right\}, \end{aligned} \tag{A25}$$

2. Density dependence relativistic mean field

The Lagrangian density of the density dependence model is:

$$\mathcal{L}_{DD} = \mathcal{L}_I + \mathcal{L}_F, \tag{A26}$$

where $\mathcal{L}_F$ is

$$\begin{aligned} \mathcal{L}_F = {} & \bar{\Psi}[i\gamma_\mu\partial^\mu - m_N]\Psi + \bar{\Delta}_\lambda[i\gamma_\mu\partial^\mu - m_\Delta]\Delta^\lambda \\ & + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) \\ & - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ & + \frac{1}{2}\left(\partial_\mu\boldsymbol{\pi}\partial^\mu\boldsymbol{\pi} - m_\pi^2\boldsymbol{\pi}^2\right) - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu \\ & + \frac{1}{2}\left(\partial_\mu\boldsymbol{\delta}\partial^\mu\boldsymbol{\delta} - m_\delta^2\boldsymbol{\delta}^2\right), \end{aligned} \tag{A27}$$

where $\mathcal{L}_I$ is

$$\begin{aligned} \mathcal{L}_I = {} & \mathcal{L}_{NN} + \mathcal{L}_{\Delta\Delta} + \mathcal{L}_{N\Delta} \\ = {} & \Gamma_\sigma(\rho)\bar{\Psi}\Psi\sigma - \Gamma_\omega(\rho)\bar{\Psi}\gamma_\mu\Psi\omega^\mu - \Gamma_\rho(\rho)\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\cdot\Psi\boldsymbol{\rho}^\mu \\ & + \frac{g_{\pi NN}}{m_\pi}\bar{\Psi}\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\Psi\partial^\mu\boldsymbol{\pi} + \Gamma_\delta(\rho)\bar{\Psi}\boldsymbol{\tau}\cdot\Psi\boldsymbol{\delta} \\ & + \Gamma_\sigma(\rho)\bar{\Delta}_\mu\Delta^\mu\sigma - \Gamma_\omega(\rho)\bar{\Delta}_\mu\gamma_\nu\Delta^\mu\omega^\nu \\ & - \Gamma_\rho(\rho)\bar{\Delta}_\mu\gamma_\nu\mathbf{T}\cdot\Delta^\mu\boldsymbol{\rho}^\nu + \frac{g_{\pi\Delta\Delta}}{m_\pi}\bar{\Delta}_\mu\gamma_\nu\gamma_5\mathbf{T}\cdot\Delta^\mu\partial^\nu\boldsymbol{\pi} \\ & + \Gamma_\delta(\rho)\bar{\Delta}_\mu\mathbf{T}\cdot\Delta^\mu\boldsymbol{\delta} + \frac{g_{\pi N\Delta}}{m_\pi}\bar{\Delta}_\mu\mathcal{T}\cdot\Psi\partial^\mu\boldsymbol{\pi} \\ & + \frac{ig_{\rho N\Delta}}{m_\rho}\bar{\Delta}_\mu\gamma_\nu\gamma_5\mathcal{T}\cdot\Psi(\partial^\nu\boldsymbol{\rho}^\mu - \partial^\mu\boldsymbol{\rho}^\nu) + h.c. \end{aligned} \tag{A28}$$

The vector and scalar potentials can be written as:

$$\Sigma_{i,DD}^0 = \Gamma_\omega\bar{\omega}^0 + \Gamma_\rho t_{3,i}\bar{\rho}_3^0 + \Sigma^r \tag{A29}$$

$$\Sigma_{i,DD}^S = -\Gamma_\sigma\bar{\sigma} - \Gamma_\delta t_{3,i}\bar{\delta}_3 \tag{A30}$$

Here Σ^r is the rearrangement term of the vector self-energy, its express is:

$$\Sigma^r = \frac{\partial\Gamma_\omega}{\rho}\bar{\omega}^0\rho + \frac{\partial\Gamma_\rho}{\partial\rho}\bar{\rho}_3^0\rho_3 - \frac{\partial\Gamma_\sigma}{\rho}\bar{\sigma}\rho_s - \frac{\partial\Gamma_\delta}{\rho}\bar{\delta}_3\rho_{s3} \tag{A31}$$

The expressions of the symmetry energy and slope of symmetry energy L for density-dependent RMF models are:

$$S(\rho)_{DD} = \frac{k_F^2}{6E_F^*} + \frac{1}{2}\rho\frac{\Gamma_\rho^2}{m_\rho^2} - \frac{1}{2}\rho\times\left(\frac{\frac{\Gamma_\delta^2}{m_\delta^2}m_N^{*2}}{E_F^{*2}\left[1+\frac{\Gamma_\delta^2}{m_\delta^2}A(\rho,m_N^*)\right]}\right), \tag{A32}$$

$$\begin{aligned} L_{DD} = {} & \frac{k_F^2}{3E_F^*}\left(1-\frac{k_F^2}{2E_F^{*2}} - \frac{k_F^3 m_N^*}{E_F^{*2}\pi^2}\frac{\partial m_N^*}{\partial\rho}\right) \\ & + \frac{3\Gamma_\rho^2}{2m_\rho^2}\rho\left(1+6\frac{\rho}{\Gamma_\rho}\frac{\partial\Gamma_\rho}{\partial\rho}\right) \\ & - \frac{1}{2}\rho\left(\frac{\frac{\Gamma_\delta^2}{m_\delta^2}m_N^{*2}}{E_F^{*2}\left[1+\frac{\Gamma_\delta^2}{m_\delta^2}A(\rho,m_N^*)\right]}\right) \\ & \times\left\{3+6\frac{\rho}{\Gamma_\delta}\frac{\partial\Gamma_\delta}{\partial\rho} - \frac{2k_F^2}{E_F^{*2}} + 6\left(1-\frac{m_N^{*2}}{E_F^{*2}}\right)\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right. \end{aligned}$$

$$-3\frac{\Gamma_\delta^2}{m_\delta^2}\frac{1}{1+\frac{\Gamma_\delta^2}{m_\delta^2}A}\left[2A\left(\frac{\rho}{\Gamma_\delta}\frac{\partial\Gamma_\delta}{\partial\rho}+\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right)+\rho\frac{k_F^2}{E_F^{*3}}\left(1-3\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right)\right]\Bigg\}, \tag{A33}$$

3. Point coupling model

Lagrangian density of the point coupling mean field model is:

$$\mathcal{L}_{PC}=\mathcal{L}_F+\mathcal{L}_I, \tag{A34}$$

where $\mathcal{L}_F$ is :

$$\mathcal{L}_F=\bar{\Psi}[i\gamma_\mu\partial^\mu-m_N]\Psi+\bar{\Delta}_\lambda[i\gamma_\mu\partial^\mu-m_\Delta]\Delta^\lambda, \tag{A35}$$

where $\mathcal{L}_I$ is :

$$\begin{aligned}\mathcal{L}_I=&-\frac{\alpha_S}{2}\left(\bar{\Psi}\Psi\right)^2-\frac{\alpha_V}{2}\left(\bar{\Psi}\gamma_\mu\Psi\right)\left(\bar{\Psi}\gamma^\mu\Psi\right)\\&-\frac{\alpha_{TV}}{2}\left(\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\Psi\right)\cdot\left(\bar{\Psi}\gamma^\mu\boldsymbol{\tau}\Psi\right)\\&-\frac{f_{\pi NN}}{m_\pi}\left(\bar{\Psi}\gamma_\mu\gamma_5\boldsymbol{\tau}\Psi\right)\cdot\partial^\mu\left(\bar{\Psi}\gamma_5\boldsymbol{\tau}\Psi\right)\\&-\frac{\alpha_{TS}}{2}\left(\bar{\Psi}\boldsymbol{\tau}\Psi\right)\cdot\left(\bar{\Psi}\boldsymbol{\tau}\Psi\right)\\&-\frac{\beta_S}{3}\left(\bar{\Psi}\Psi\right)^3-\frac{\gamma_S}{4}\left(\bar{\Psi}\Psi\right)^4-\frac{\gamma_V}{4}\left(\bar{\Psi}\gamma_\mu\Psi\bar{\Psi}\gamma^\mu\Psi\right)^2\\&-\frac{\alpha_{TV}}{4}\left(\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\Psi\cdot\bar{\Psi}\gamma^\mu\boldsymbol{\tau}\Psi\right)^2\\&+[\eta_1+\eta_2\left(\bar{\Psi}\Psi\right)]\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\gamma_\mu\Psi\right)\left(\bar{\Psi}\gamma^\mu\Psi\right)\\&-\eta_3\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\Psi\right)\cdot\left(\bar{\Psi}\gamma^\mu\boldsymbol{\tau}\Psi\right)\\&-\frac{\alpha_S}{2}[\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\Psi\right)+\left(\bar{\Psi}\Psi\right)\left(\bar{\Delta}_\mu\Delta^\mu\right)]\\&-\frac{\alpha_V}{2}[\left(\bar{\Delta}_\mu\gamma_\nu\Delta^\mu\right)\left(\bar{\Psi}\gamma^\nu\Psi\right)+\left(\bar{\Psi}\gamma_\nu\Psi\right)\left(\bar{\Delta}_\mu\gamma^\nu\Delta^\mu\right)]\\&-\frac{\alpha_{TV}}{2}[\left(\bar{\Delta}_\mu\gamma_\nu\mathbf{T}\Delta^\mu\right)\cdot\left(\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\\&+\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\right)\cdot\left(\bar{\Delta}_\mu\gamma^\nu\mathbf{T}\Delta^\mu\right)]\\&-\frac{\alpha_{TS}}{2}[\left(\bar{\Delta}_\mu\mathbf{T}\Delta^\mu\right)\cdot\left(\bar{\Psi}\boldsymbol{\tau}\Psi\right)+\left(\bar{\Psi}\boldsymbol{\tau}\Psi\right)\cdot\left(\bar{\Delta}_\mu\mathbf{T}\Delta^\mu\right)]\\&-\frac{\beta_S}{3}[\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\Psi\right)^2+\left(\bar{\Psi}\Psi\right)\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)^2\left(\bar{\Delta}_\mu\Delta^\mu\right)]\\&-\frac{\gamma_S}{4}[\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\Psi\right)^3+\left(\bar{\Psi}\Psi\right)\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\Psi\right)^2\\&+\left(\bar{\Psi}\Psi\right)^2\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\Psi\right)+\left(\bar{\Psi}\Psi\right)^3\left(\bar{\Delta}_\mu\Delta^\mu\right)]\\&-\frac{\gamma_V}{4}[\left(\bar{\Delta}_\mu\gamma_\nu\Delta^\mu\bar{\Psi}\gamma^\nu\Psi\right)\left(\bar{\Psi}\gamma_\nu\Psi\bar{\Psi}\gamma^\nu\Psi\right)\\&+\left(\bar{\Psi}\gamma_\nu\Psi\bar{\Delta}_\mu\gamma^\nu\Delta^\mu\right)\left(\bar{\Psi}\gamma_\nu\Psi\bar{\Psi}\gamma^\nu\Psi\right)\\&+\left(\bar{\Psi}\gamma_\nu\Psi\bar{\Psi}\gamma^\nu\Psi\right)\left(\bar{\Psi}\gamma_\nu\Psi\bar{\Delta}_\mu\gamma^\nu\Delta^\mu\right)\\&+\left(\bar{\Psi}\gamma_\nu\Psi\bar{\Psi}\gamma^\nu\Psi\right)\left(\bar{\Delta}_\mu\gamma_\nu\Delta^\mu\bar{\Psi}\gamma^\nu\Psi\right)]\\&-\frac{\alpha_{TV}}{4}[\left(\bar{\Delta}_\mu\gamma_\nu\mathbf{T}\Delta^\mu\cdot\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\cdot\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\\&+\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\cdot\bar{\Delta}_\mu\gamma^\nu\mathbf{T}\Delta^\mu\right)\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\cdot\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\\&+\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\cdot\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\left(\bar{\Delta}_\mu\gamma_\nu\mathbf{T}\Delta^\mu\cdot\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\\&+\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\cdot\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\cdot\bar{\Delta}_\mu\gamma^\nu\mathbf{T}\Delta^\mu\right)]\\&-\eta_1[\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\gamma_\nu\Psi\right)\left(\bar{\Psi}\gamma^\nu\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)\left(\bar{\Delta}_\mu\gamma_\nu\Delta^\mu\right)\left(\bar{\Psi}\gamma^\nu\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\gamma_\nu\Psi\right)\left(\bar{\Delta}_\mu\gamma^\nu\Delta^\mu\right)]\\&-\eta_2[\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\gamma_\nu\Psi\right)\left(\bar{\Psi}\gamma^\nu\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\gamma_\nu\Psi\right)\left(\bar{\Psi}\gamma^\nu\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\Psi\right)\left(\bar{\Delta}_\mu\gamma_\nu\Delta^\mu\right)\left(\bar{\Psi}\gamma^\nu\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\gamma_\nu\Psi\right)\left(\bar{\Delta}_\mu\gamma^\nu\Delta^\mu\right)]\\&-\eta_3[\left(\bar{\Delta}_\mu\Delta^\mu\right)\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\right)\cdot\left(\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)\left(\bar{\Delta}_\mu\gamma_\nu\mathbf{T}\Delta^\mu\right)\cdot\left(\bar{\Psi}\gamma^\nu\boldsymbol{\tau}\Psi\right)\\&+\left(\bar{\Psi}\Psi\right)\left(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi\right)\cdot\left(\bar{\Delta}_\mu\gamma^\nu\mathbf{T}\Delta^\mu\right)]\\&-\frac{f_{\pi NN}}{m_\pi}\left(\bar{\Delta}_\mu\gamma_\nu\gamma_5\boldsymbol{\tau}\Delta^\nu\right)\cdot\partial^\mu\left(\bar{\Psi}\gamma_5\boldsymbol{\tau}\Psi\right)\\&+\frac{g_{\pi N\Delta}}{m_\pi}\bar{\Delta}_\mu\mathcal{T}\cdot\Psi\partial^\mu\left(\bar{\Psi}\gamma_5\boldsymbol{\tau}\Psi\right)\\&+\frac{ig_{\rho N\Delta}}{m_\rho}\bar{\Delta}_\mu\gamma_\nu\gamma_5\mathcal{T}\cdot\Psi\left(\partial^\nu(\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\Psi)-\partial^\mu(\bar{\Psi}\gamma_\nu\boldsymbol{\tau}\Psi)\right)\\&+h.c.\end{aligned} \tag{A36}$$

The vector and scalar potentials can be expressed as:

$$\begin{aligned}\Sigma_{i,PC}^0=&\alpha_V\rho+\alpha_{TV}\rho_3t_{3,i}+\gamma_{TV}\rho^3+\gamma_{TV}\rho_3^3t_{3,i}\\&+2(\eta_1+\eta_2\rho_s)\rho_s\rho+2\eta_3\rho_s\rho_3t_{3,i}\end{aligned} \tag{A37}$$

$$\begin{aligned}\Sigma_{i,PC}^S=&\alpha_S\rho_S+\beta_S\rho_s^2+\gamma_S\rho_s^3+\eta_1\rho^2+2\eta_2\rho_s\rho^2\\&+\eta_3\rho_3^2+\alpha_{TS}\rho_{s3}t_{3,i}\end{aligned} \tag{A38}$$

The expressions of the symmetry energy and slope of symmetry energy L for point-coupling RMF models are:

$$\begin{aligned}S(\rho)_{PC}=&\frac{k_F^2}{6E_F^*}+\frac{1}{2}\alpha_V\rho+\eta_3\rho_s\rho\\&+\frac{1}{2}\alpha_{TS}\rho\left(\frac{m_N^{*2}}{E_F^{*2}[1-\alpha_{TS}A(\rho,m_N^*)]}\right),\end{aligned} \tag{A39}$$

$$
\begin{aligned}
L_{PC} = & \frac{k_F^2}{3E_F^*}\left(1-\frac{k_F^2}{2E_F^{*2}}-\frac{k_F^3 m_N^*}{E_F^{*2}\pi^2}\frac{\partial m_N^*}{\partial\rho}\right) \\
& +\frac{3}{2}\alpha_V\rho+3\eta_3\rho_s\rho+3\eta_3\rho^2\frac{\partial\rho_s}{\partial\rho} \\
& +\frac{1}{2}\alpha_{TS}\rho\left(\frac{m_N^{*2}}{E_F^{*2}[1-\alpha_{TS}A(\rho,m_N^*)]}\right) \\
& \times\left\{3-\frac{2k_F^2}{E_F^{*2}}+6\left(1-\frac{m_N^{*2}}{E_F^{*2}}\right)\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right. \\
& +3\alpha_{TS}\frac{1}{1-\alpha_{TS}A}\left[2A\left(\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right)\right. \\
& \left.\left.+\rho\frac{k_F^2}{E_F^{*3}}\left(1-3\frac{\rho}{m_N^*}\frac{\partial m_N^*}{\partial\rho}\right)\right]\right\}. \qquad \text{(A40)}
\end{aligned}
$$

APPENDIX B: IN-MEDIUM $NN \to N\Delta$ CROSS SECTION

Applying quasiparticle approximation [53], the in-medium cross sections are introduced via the replacement of the vacuum plane waves of the initial and final particles by the plane waves obtained by solution of the nucleon and Δ equations of motion with scalar and vector fields. In detail, the matrix elements $\mathcal{M}^*$ for the inelastic scattering process $NN \to N\Delta$ are obtained by replacing the nucleon and Δ masses and momenta in free space with their effective masses and kinetic momenta [24], i.e., $m \to m^*$ and $p^\mu \to p^{*\mu}$. As in Ref. [24], all the calculations performed in this work are are performed for colliding nucleons with their center-of-mass frame coinciding with the nuclear matter rest frame.

The Feynmann diagrams corresponding to the inelastic-scattering $NN \to N\Delta$ processes are shown in Fig. B1, which include the direct and exchange processes. The $\mathcal{M}^*$-matrix derived from the interaction Lagrangian Eq. (A3) can be written by using the standard procedure [10],

$$
\mathcal{M}^* = \mathcal{M}_d^{*\pi} - \mathcal{M}_e^{*\pi} + \mathcal{M}_d^{*\rho} - \mathcal{M}_e^{*\rho}, \qquad \text{(B1)}
$$

where

$$
\begin{aligned}
\mathcal{M}_d^{*\pi} = & -i\frac{g_{\pi NN}g_{\pi N\Delta}I_d}{m_\pi^2(Q_d^{*2}-m_\pi^2)}[\bar{\Psi}(p_3^*)\gamma_\mu\gamma_5 Q_d^{*\mu}\Psi(p_1^*)] \\
& \times[\bar{\Delta}_\nu(p_4^*)Q_d^{*\nu}\Psi(p_2^*)] \qquad \text{(B2)}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{M}_d^{*\rho} = & i\frac{\Gamma_{\rho NN}g_{\rho N\Delta}I_d}{m_\rho}[\bar{\Psi}(p_3^*)\gamma_\mu\Psi(p_1^*)] \\
& \times\frac{g^{\mu\tau}-Q_d^{*\mu}Q_d^{*\tau}/m_\rho^2}{Q_d^{*2}-m_\rho^2} \\
& \times[\bar{\Delta}_\sigma(p_4^*)\gamma_\lambda\gamma_5(Q_d^{*\lambda}\delta_{\sigma\tau}-Q_d^{*\sigma}\delta_{\lambda\tau})\Psi(p_2^*)]\,. \qquad \text{(B3)}
\end{aligned}
$$

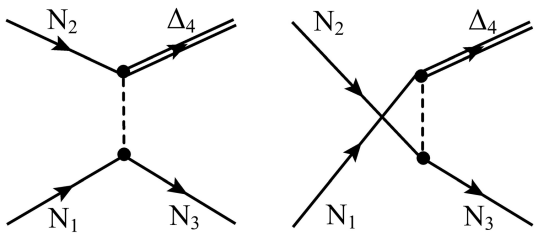

Fig. B1. The left diagram is the direct term and the right is the exchange term of the Feynmann diagram.

For the direct term, $Q_d^{*\mu} = p_3^{*\mu} - p_1^{*\mu}$, while the exchange term $\mathcal{M}_e^*$ is obtained by swapping $p_1^{*\mu} \longleftrightarrow p_2^{*\mu}$ and $Q_e^{*\mu} = p_3^{*\mu} - p_2^{*\mu}$. The isospin factors I_d, I_e are given in Ref. [10].

The in-medium $NN \to N\Delta$ cross section is the averaged two-body cross section, taking into account the mass distribution of the Δ resonance as a short-lived state. It can be expressed as:

$$
\sigma^*_{NN\to N\Delta} = \int_{m^*_{\Delta,\min}}^{m^*_{\Delta,\max}} dm^*_\Delta f(m^*_\Delta)\tilde{\sigma}^*(m^*_\Delta), \qquad \text{(B4)}
$$

where $\tilde{\sigma}^*(m^*_\Delta)$ is the in-medium elementary two-body cross section. In the center-of-mass frame of colliding nucleons, it reads

$$
\tilde{\sigma}^*(m^*_\Delta) = \frac{1}{64\pi^2}\int\frac{|\mathbf{p}^*_{\text{out, c.m.}}|}{\sqrt{s^*_{\text{in}}}\sqrt{s^*_{\text{out}}}|\mathbf{p}^*_{\text{in, c.m.}}|}\overline{|\mathcal{M}^*|^2}d\Omega, \qquad \text{(B5)}
$$

where $\mathbf{p}^*_{\text{in, c.m.}}$ and $\mathbf{p}^*_{\text{out, c.m.}}$ are the momenta of incoming (1 and 2) and outgoing particles (3 and 4), and $s^*_{\text{in}} = (p_1^* + p_2^*)^2$, and $s^*_{\text{out}} = (p_3^* + p_4^*)^2$.

Here $\overline{|\mathcal{M}^*|^2} = \frac{1}{(2s_1+1)(2s_2+1)}\sum_{s_1s_2s_3s_4}|\mathcal{M}^*|^2$ is,

$$
\begin{aligned}
& \sum_{s_1s_2s_3s_4}|\mathcal{M}^*|^2 \\
= & \sum_{s_1s_2s_3s_4}\{|\mathcal{M}_d^{*\pi}|^2 - \mathcal{M}_d^{*\pi\dagger}\mathcal{M}_e^{*\pi} - \mathcal{M}_e^{*\pi\dagger}\mathcal{M}_d^{*\pi} + |\mathcal{M}_e^{*\pi}|^2 \\
& + |\mathcal{M}_d^{*\rho}|^2 - \mathcal{M}_d^{*\rho\dagger}\mathcal{M}_e^{*\rho} - \mathcal{M}_e^{*\rho\dagger}\mathcal{M}_d^{*\rho} + |\mathcal{M}_e^{*\rho}|^2 \\
& + \mathcal{M}_d^{*\pi\dagger}\mathcal{M}_d^{*\rho} - \mathcal{M}_d^{*\pi\dagger}\mathcal{M}_e^{*\rho} - \mathcal{M}_e^{*\pi\dagger}\mathcal{M}_d^{*\rho} + \mathcal{M}_e^{*\pi\dagger}\mathcal{M}_e^{*\rho} \\
& + \mathcal{M}_d^{*\rho\dagger}\mathcal{M}_d^{*\pi} - \mathcal{M}_d^{*\rho\dagger}\mathcal{M}_e^{*\pi} - \mathcal{M}_e^{*\rho\dagger}\mathcal{M}_d^{*\pi} + \mathcal{M}_e^{*\rho\dagger}\mathcal{M}_e^{*\pi}\}. \qquad \text{(B6)}
\end{aligned}
$$

where the $\mathcal{M}^*$-matrix is from exchange by π and ρ mesons, and the detail calculations can be found in Ref. [27]. Here, we show the calculation of $\sum_{s_1s_2s_3s_4}|\mathcal{M}_d^{*\pi}|^2$ as an example in the following:

$$\begin{aligned}\sum_{s_1s_2s_3s_4}|\mathcal{M}_d^{*\pi}|^2 &= \left(\frac{g_{\pi NN}g_{\pi N\Delta}I_d}{m_\pi^2(Q_d^{*2}-m_\pi^2)}\right)^2\\ &\times\sum_{s_1s_2s_3s_4}[\Psi(p_1^*)\bar{\Psi}(p_1^*)\gamma_\mu\gamma_5Q_d^{*\mu}\Psi(p_3^*)\bar{\Psi}(p_3^*)\gamma_\sigma\gamma_5Q_d^{*\sigma}]\\ &\times[\Psi(p_2^*)\bar{\Psi}(p_2^*)Q_d^{*\nu}\Delta_\nu(p_4^*)\bar{\Delta}_\tau(p_4^*)Q_d^{*\tau}]\\ &= \left(\frac{g_{\pi NN}g_{\pi N\Delta}I_d}{m_\pi^2(t^*-m_\pi^2)}\right)^2\\ &\times\frac{2(m_{N_1}^*+m_{N_3}^*)^2((m_{N_1}^*-m_{N_3}^*)^2-t^*)}{3m_{\Delta_4}^{*2}}\\ &\times\left((m_{\Delta_4}^*-m_{N_2}^*)^2-t^*\right)\left((m_{N_2}^*+m_{\Delta_4}^*)^2-t^*\right)^2\end{aligned}\tag{B7}$$

where $t=Q_d^{*2}$, for $|\mathcal{M}_e^{*\pi}|^2$ is $N_1\longleftrightarrow N_2$. In Eq. (B5),the key element for the calculation of the cross section is the energy-momentum conservation in terms of the incoming ($p_{1,2}^\mu$) and outgoing momenta ($p_{3,4}^\mu$) of the particles. From the viewpoint of kinetic momentum, the energy-momentum conservation can be written as: $p_1^\mu+p_2^\mu=p_3^\mu+p_4^\mu$ can be expressed as $p_1^{*\mu}+\Sigma_1^{*\mu}+p_2^{*\mu}+\Sigma_2^{*\mu}=p_3^{*\mu}+\Sigma_3^{*\mu}+p_4^{*\mu}+\Sigma_4^{*\mu}$, $p_1^{*\mu}+p_2^{*\mu}=p_3^{*\mu}+p_4^{*\mu}-\Delta\Sigma^\mu$, where $\Delta\Sigma^\mu=\Sigma_1^\mu+\Sigma_2^\mu-\Sigma_3^\mu-\Sigma_4^\mu$ is the kinetic momentum change between the initial and final states. The change in effective energy is expressed as $\Delta\Sigma^0=\Sigma_1^0+\Sigma_2^0-\Sigma_3^0-\Sigma_4^0$, which is the same the formula in Ref. [27, 54]. The similar issue also exists in the calculation of $m_{\rm min}^*$, $m_{\rm max}^*$ and $\Gamma(m_\Delta^*)$ which are described in the following. Consequently, $p_1^{*0}+p_2^{*0}$ may differ from $p_3^{*0}+p_4^{*0}$, and $s_{in}^*\neq s_{out}^*$ in Eq. (B5), and they are related according to the following relationship,

$$\sqrt{s}=\sqrt{s_{in}^*}+\Sigma_{N_1}^0+\Sigma_{N_2}^0=\sqrt{s_{out}^*}+\Sigma_{N_3}^0+\Sigma_{\Delta_4}^0.\tag{B8}$$

It is derived from

$$\begin{aligned}s&=(p_{N_1}+p_{N_2})^2\\ &=(\sqrt{m_{N_1}^{*2}+\mathbf{p}_{N_1}^{*2}}+\sqrt{m_{N_2}^{*2}+\mathbf{p}_{N_2}^{*2}}+\Sigma_{N_1}^0+\Sigma_{N_2}^0)^2\\ &\quad-(\mathbf{p}_{N_1}^*+\mathbf{p}_{N_2}^*)^2\\ &=(p_{N_3}+p_{\Delta_4})^2\\ &=(\sqrt{m_{N_3}^{*2}+\mathbf{p}_{N_3}^{*2}}+\sqrt{m_{\Delta_4}^{*2}+\mathbf{p}_{\Delta_4}^{*2}}+\Sigma_{N_3}^0+\Sigma_{\Delta_4}^0)^2\\ &\quad-(\mathbf{p}_{N_3}^*+\mathbf{p}_{\Delta_4}^*)^2\end{aligned}\tag{B9}$$

where $\mathbf{p}_{N_1}^*=-\mathbf{p}_{N_2}^*$ and $\mathbf{p}_{N_3}^*=-\mathbf{p}_{\Delta_4}^*$ in the center-of-mass frame.

The value of $m_{\Delta,\rm min}^*$ in the cross-section formula is determined by the $\Delta\to N+\pi$ in isospin asymmetric nuclear matter as in Refs. [27, 55], where both the N and π are at rest. Additionally, the modification of the scalar and vector self-energies in this isospin exchange process must also be taken into account. Thus,

$$m_{\Delta,\rm min}^*=m_N^*+m_\pi-\Delta\Sigma_d^0,\tag{B10}$$

with $\Delta\Sigma_d^0=\Sigma_\Delta^0-\Sigma_N^0$. The $m_{\Delta,\rm max}^*$ is evaluated from $NN\to N\Delta$ for producing N and Δ at rest. This leads to:

$$m_{\Delta,\rm max}^*=\sqrt{s}-m_{N_3}^*-\Sigma_{N_3}^0-\Sigma_{\Delta_4}^0.\tag{B11}$$

The in-medium Δ mass distribution $f(m_\Delta^*)$ is another crucial component of in-medium $NN\to N\Delta$ cross section, for which proper energy conservation is also required, as $f(m_\Delta^*)$ is related to the $\Delta\to N+\pi$ process in isospin asymmetric nuclear matter. In this paper, the spectral function of Δ is taken from Ref. [24],

$$f(m_\Delta^*)=\frac{2}{\pi}\frac{m_\Delta^{*2}\Gamma(m_\Delta^*)}{(m_{0,\Delta}^{*2}-m_\Delta^{*2})^2+m_\Delta^{*2}\Gamma^2(m_\Delta^*)}.\tag{B12}$$

Here, $m_{0,\Delta}^*$ is the effective pole mass of Δ. The decay width $\Gamma(m_\Delta^*)$ is taken as the parameterization form [24]

$$\Gamma(m_\Delta^*)=\Gamma_0\frac{q^3(m_\Delta^*,m_N^*,m_\pi^*)}{q^3(m_{0,\Delta}^*,m_N^*,m_\pi^*)}\frac{q^3(m_{0,\Delta}^*,m_N^*,m_\pi^*)+\eta^2}{q^3(m_\Delta^*,m_N^*,m_\pi^*)+\eta^2}\frac{m_{0,\Delta}^*}{m_\Delta^*},\tag{B13}$$

where

$$q(m_\Delta^*,m_N^*,m_\pi^*)=\sqrt{\frac{\left((m_\Delta^*+\Sigma_\Delta^0-\Sigma_N^0)^2+m_N^{*2}-m_\pi^{*2}\right)^2}{4(m_\Delta^*+\Sigma_\Delta^0-\Sigma_N^0)^2}-m_N^{*2}}.\tag{B14}$$

The coefficients of Γ_0=0.118 GeV and η=0.2 GeV/c are used in the above parameterization formula.

The form factors are adopted to effectively consider the contributions from high-order terms and the finite size of baryons [10, 56], which read

$$F_N(t^*)=\frac{\Lambda_N^2}{\Lambda_N^2-t^*}exp\left(-b\sqrt{s^*-4m_N^{*2}}\right)\tag{B15}$$

$$F_\Delta(t^*)=\frac{\Lambda_\Delta^2}{\Lambda_\Delta^2-t^*}.\tag{B16}$$

Here $F_N(t^*)$ is the form factor for nucleon-meson-nucleon, and $F_\Delta(t^*)$ for nucleon-meson-Δ coupling, b=0.046 GeV^{-1} for both ρNN and πNN coupling. The cutoff parameter $\Lambda_{\pi NN}\approx1$ GeV, $\Lambda_{\rho NN}$ and $\Lambda_{\pi N\Delta}$ are determined by best fitting the data of $NN\to N\Delta$ cross section in free

space ranging from $\sqrt{s}$=2.0 to 5 GeV [45]. Here, $\Lambda_{\rho N\Delta}$ is determined based on the relationship $\Lambda_{\rho N\Delta} = \Lambda_{\rho NN}\frac{\Lambda_{\pi N\Delta}}{\Lambda_{\pi NN}}$ as in [10]. Concerning the coupling constant $g_{\rho N\Delta}$, we use $g_{\rho N\Delta} \approx \frac{\sqrt{3}}{2}\Gamma_{\rho NN}\frac{m_\rho}{m_N}$ which are derived from the static quark model [10]. The cutoff parameters used in calculations of in-medium $NN \to N\Delta$ cross sections are listed in Table C1 in Appendix C.

APPENDIX C: THE PARAMETERS FOR DIFFERENT RMF MODELS

For the coupling constant parameters of $g_{m\Delta\Delta}$(where $m = \sigma,\omega,\rho,\delta$), we adopt $g_m = g_{m\Delta\Delta} = g_{mNN}$ consistent with the approach used in many studies involving transport models [11, 24, 26]. The parameters used in the effective Lagrangian, $g_{\pi NN}$=1.008, $g_{\pi N\Delta}$=2.202, m_π=138 MeV, m_N=939 MeV, $m_{0,\Delta}$=1232 MeV.

Table C1. The saturation properties of all RMF models are used in this work. Excepting for m_N^*/m_N and $m_{0,\Delta}^*/m_{0,\Delta}$ in dimensionless, and ρ_0 in fm^{-3}, all entries are in MeV. All $\Lambda_{\rho NN}$ = 1000 MeV, except for $\Lambda_{\rho NN}$ = 798, 650 and 580 MeV for FSUGOLD5, DDMEδ and DDRH$_{\rho\delta}$.

Model	E_0	ρ_0	K_0	J	L	K_{sym}	m_N^*/m_N	$m_{0,\Delta}^*/m_{0,\Delta}$	$\Lambda_{\pi N\Delta}$
Nonlinear models									
E [57]	−16.35	0.150	210.95	38.58	124.69	133.52	0.578	0.679	417
ER [57]	−16.25	0.149	215.91	39.41	126.63	128.12	0.582	0.682	416
NL1 [58]	−16.42	0.152	212.35	43.54	140.37	143.39	0.572	0.674	415
NL3 [59]	−16.24	0.148	269.91	37.34	118.32	100.53	0.596	0.692	417
NL3-II [59]	−16.26	0.149	270.62	37.67	119.57	103.19	0.593	0.690	417
NL3* [60]	−16.31	0.150	258.76	38.70	122.72	105.72	0.594	0.690	417
NL4 [61]	−16.16	0.148	273.33	36.34	115.31	100.41	0.595	0.692	417
NLC [62]	−15.77	0.148	221.76	35.23	108.52	76.14	0.633	0.720	417
NLB1 [58]	−15.80	0.162	276.73	32.94	102.12	75.61	0.621	0.711	420
NLB2 [58]	−15.80	0.162	239.96	32.93	110.57	157.15	0.557	0.662	421
NLRA1 [63]	−16.15	0.147	284.42	36.44	115.31	95.56	0.597	0.693	417
NLS [64]	−16.45	0.150	262.98	42.08	131.61	94.27	0.604	0.698	415
P-067 [65]	−16.31	0.160	245.72	41.80	124.81	48.93	0.665	0.745	416
P-070 [65]	−16.25	0.160	228.23	41.04	119.74	26.04	0.702	0.773	416
P-075 [65]	−16.51	0.170	253.33	42.17	119.16	−2.19	0.755	0.813	416
P-080 [65]	−15.84	0.160	251.71	39.28	108.78	−14.06	0.800	0.847	416
GL1 [66]	−16.30	0.153	200.08	32.50	94.68	33.08	0.700	0.772	418
GL2 [66]	−16.31	0.153	199.92	32.50	91.52	8.74	0.750	0.810	418
GL3 [66]	−16.31	0.153	199.87	32.50	89.03	−8.43	0.800	0.848	417
GL4 [66]	−16.31	0.153	249.88	32.50	94.31	25.23	0.700	0.772	418
GL5 [66]	−16.31	0.153	249.81	32.50	91.19	2.63	0.750	0.810	418
GL6 [66]	−16.31	0.153	249.90	32.50	88.73	−12.93	0.800	0.848	417
GL7 [66]	−16.30	0.153	299.99	32.50	93.94	17.94	0.700	0.772	418
GL8 [66]	−16.31	0.153	299.84	32.50	90.86	−2.91	0.750	0.810	418
GL82 [67]	−16.00	0.145	285.41	36.22	101.28	−8.06	0.773	0.827	416
GL9 [66]	−16.31	0.153	299.89	32.50	88.44	−16.84	0.800	0.848	417
GM1 [68]	−16.34	0.153	299.85	32.50	93.96	17.96	0.700	0.772	418
GM2 [68]	−16.31	0.153	299.94	32.50	89.34	−11.99	0.780	0.832	418
GM3 [68]	−16.30	0.153	239.93	32.50	89.71	−6.46	0.780	0.832	418
GPS1 [69]	−15.98	0.150	250.46	32.52	88.96	−12.54	0.800	0.848	417

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Table C1-continued from previous page

Model	E_0	ρ_0	K_0	J	L	K_{sym}	m_N^*/m_N	$m_{0,\Delta}^*/m_{0,\Delta}$	$\Lambda_{\pi N\Delta}$
GPS2 [69]	−15.96	0.150	300.67	32.52	88.66	−16.42	0.800	0.848	417
NLρA [29]	−16.00	0.160	240.16	30.34	84.52	3.38	0.750	0.809	419
NLρB [29]	−16.30	0.148	271.55	33.70	106.87	95.85	0.600	0.695	418
RMF301 [70]	−16.30	0.153	253.79	32.50	89.87	−6.24	0.775	0.829	418
RMF302 [70]	−16.30	0.153	249.64	32.50	89.65	−7.35	0.780	0.832	418
RMF303 [70]	−16.30	0.153	248.80	32.50	89.61	−7.57	0.781	0.833	418
RMF304 [70]	−16.30	0.153	247.97	32.50	89.57	−7.78	0.782	0.834	418
RMF305 [70]	−16.30	0.153	246.30	32.50	89.49	−8.21	0.784	0.835	418
RMF306 [70]	−16.30	0.153	244.62	32.50	89.40	−8.63	0.786	0.837	418
RMF307 [70]	−16.30	0.153	243.77	32.50	89.36	−8.83	0.787	0.838	418
RMF308 [70]	−16.30	0.153	242.94	32.50	89.32	−9.04	0.788	0.838	418
RMF309 [70]	−16.30	0.153	241.24	32.50	89.24	−9.45	0.790	0.840	418
RMF310 [70]	−16.30	0.153	238.68	32.50	89.12	−10.04	0.793	0.842	418
RMF311 [70]	−16.30	0.153	237.82	32.50	89.08	−10.24	0.794	0.843	417
RMF312 [70]	−16.30	0.153	236.96	32.50	89.04	−10.43	0.795	0.844	417
RMF313 [70]	−16.30	0.153	235.24	32.50	88.96	−10.82	0.797	0.845	417
RMF314 [70]	−16.30	0.153	234.39	32.50	88.92	−11.01	0.798	0.846	417
RMF315 [70]	−16.30	0.153	233.94	32.50	88.90	−11.10	0.799	0.846	417
RMF316 [70]	−16.30	0.153	233.51	32.50	88.88	−11.20	0.799	0.847	417
RMF317 [70]	−16.30	0.153	232.65	32.50	88.84	−11.38	0.800	0.848	417
RMF401 [70]	−16.31	0.153	229.87	32.50	93.78	23.04	0.710	0.779	418
RMF402 [70]	−16.31	0.153	231.87	32.50	93.77	22.74	0.710	0.779	418
RMF403 [70]	−16.31	0.153	229.88	32.50	93.12	18.06	0.720	0.787	418
RMF404 [70]	−16.47	0.153	230.42	32.50	93.14	17.86	0.720	0.786	418
RMF405 [70]	−16.31	0.153	233.88	32.50	93.09	17.50	0.720	0.787	418
RMF406 [70]	−16.31	0.153	233.92	32.50	89.75	−5.80	0.780	0.832	418
RMF407 [70]	−16.31	0.153	229.89	32.50	92.50	13.42	0.730	0.794	418
RMF408 [70]	−16.31	0.153	231.89	32.50	92.48	13.15	0.730	0.794	418
RMF409 [70]	−16.31	0.153	233.89	32.50	92.47	12.88	0.730	0.794	418
RMF410 [70]	−16.31	0.153	235.89	32.50	92.45	12.62	0.730	0.794	418
RMF411 [70]	−16.31	0.153	229.90	32.50	91.90	9.09	0.740	0.802	418
RMF412 [70]	−16.31	0.153	231.90	32.50	91.88	8.84	0.740	0.802	418
RMF413 [70]	−16.31	0.153	233.90	32.50	91.87	8.58	0.740	0.802	418
RMF414 [70]	−16.31	0.153	235.90	32.50	91.86	8.33	0.740	0.802	418
RMF415 [70]	−16.30	0.153	229.91	32.50	91.33	5.06	0.750	0.809	418
RMF416 [70]	−16.30	0.153	231.91	32.50	91.31	4.82	0.750	0.809	418
RMF417 [70]	−16.30	0.153	233.91	32.50	91.30	4.58	0.750	0.809	418
RMF418 [70]	−16.30	0.153	235.91	32.50	91.29	4.34	0.750	0.809	418
RMF419 [70]	−16.31	0.153	229.91	32.50	90.79	1.31	0.760	0.817	418
RMF420 [70]	−16.31	0.153	231.91	32.50	90.77	1.09	0.760	0.817	418
RMF421 [70]	−16.31	0.153	233.91	32.50	90.76	0.86	0.760	0.817	418

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Table C1-continued from previous page

Model	E_0	ρ_0	K_0	J	L	K_{sym}	m_N^*/m_N	$m_{0,\Delta}^*/m_{0,\Delta}$	$\Lambda_{\pi N\Delta}$
RMF422 [70]	−16.31	0.153	229.92	32.50	90.27	−2.17	0.770	0.825	418
RMF423 [70]	−16.31	0.153	231.91	32.50	90.26	−2.38	0.770	0.825	418
RMF424 [70]	−16.30	0.153	245.93	32.50	89.21	−9.88	0.790	0.840	418
RMF425 [70]	−16.30	0.153	247.94	32.50	89.20	−10.06	0.790	0.840	418
RMF426 [70]	−16.30	0.153	249.94	32.50	89.19	−10.24	0.790	0.840	418
RMF427 [70]	−16.30	0.153	235.94	32.50	88.83	−11.67	0.800	0.848	417
RMF428 [70]	−16.30	0.153	237.94	32.50	88.81	−11.85	0.800	0.848	417
RMF429 [70]	−16.30	0.153	239.94	32.50	88.80	−12.02	0.800	0.848	417
RMF430 [70]	−16.30	0.153	241.94	32.50	88.79	−12.19	0.800	0.848	417
RMF431 [70]	−16.30	0.153	243.94	32.50	88.78	−12.36	0.800	0.848	417
RMF432 [70]	−16.30	0.153	245.94	32.50	88.77	−12.53	0.800	0.848	417
RMF433 [70]	−16.30	0.153	247.94	32.50	88.75	−12.70	0.800	0.848	417
RMF434 [70]	−16.30	0.153	249.94	32.50	88.74	−12.87	0.800	0.848	417
Q1 [71]	−16.10	0.148	242.19	36.46	115.77	105.77	0.597	0.693	417
SMFT2 [72]	−13.85	0.162	210.02	17.37	52.72	60.28	0.656	0.738	430
S271 [38]	−16.24	0.148	270.94	35.03	101.91	22.28	0.700	0.771	417
SRK3M5 [73]	−16.00	0.150	299.95	23.50	82.46	146.79	0.550	0.657	425
DJM [72]	−14.81	0.172	245.71	20.23	63.03	32.62	0.569	0.671	430
HD [74]	−16.22	0.177	283.50	35.67	105.86	44.51	0.666	0.746	419
MS1 [75]	−15.75	0.148	249.97	35.00	106.76	38.56	0.600	0.695	418
MS3 [76]	−15.75	0.148	247.80	34.91	102.11	−0.10	0.601	0.696	418
NLSV1 [77]	−16.26	0.149	269.49	37.28	114.61	58.91	0.613	0.705	417
NLSV2 [77]	−16.24	0.147	293.95	36.84	111.78	39.60	0.618	0.709	417
TM1 [78]	−16.26	0.145	279.55	36.84	110.61	33.55	0.635	0.722	416
PK1 [79]	−16.22	0.148	283.39	37.61	115.78	55.17	0.605	0.700	417
Z271 [38]	−16.24	0.148	270.96	33.30	91.02	−16.40	0.800	0.848	417
hybrid [80]	−16.24	0.148	228.75	37.24	118.41	110.50	0.596	0.692	417
Z271* [81]	−16.24	0.148	268.69	40.18	83.52	−197.69	0.800	0.848	413
HC [74]	−15.75	0.169	233.88	31.06	58.60	−98.75	0.679	0.756	417
XS [76]	−16.30	0.148	228.11	31.78	54.85	−28.76	0.601	0.696	410
BKA20 [82]	−16.09	0.146	236.89	32.24	75.39	−15.04	0.642	0.727	412
BKA22 [82]	−16.08	0.147	223.09	33.13	78.67	−8.84	0.608	0.701	410
BKA24 [82]	−16.13	0.147	225.97	34.18	84.77	−14.95	0.603	0.698	413
FSUGOLD [83]	−16.28	0.148	228.56	32.54	60.38	−51.45	0.611	0.703	413
FSUGOLD4 [84]	−16.53	0.148	228.95	31.47	51.98	−16.12	0.610	0.703	410
FSUGOLD5 [84]	−16.92	0.148	229.53	30.56	45.66	23.28	0.610	0.703	413
FSUGZ00 [85]	−16.03	0.149	241.74	31.47	62.27	−3.22	0.605	0.699	410
FSUGZ03 [85]	−16.07	0.147	230.73	31.50	63.86	−11.75	0.603	0.698	410
FSUGZ06 [85]	−16.05	0.146	226.48	31.22	62.53	−24.49	0.607	0.700	410
IU-FSU [86]	−16.40	0.155	233.39	31.34	47.35	28.99	0.609	0.702	410
NL3V1 [87]	−16.24	0.148	269.60	36.01	101.08	0.62	0.596	0.692	416

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Table C1-continued from previous page

Model	E_0	ρ_0	K_0	J	L	K_{sym}	m_N^*/m_N	$m_{0,\Delta}^*/m_{0,\Delta}$	$\Lambda_{\pi N\Delta}$
NL3V2 [87]	−16.24	0.148	269.60	34.93	87.64	−46.25	0.596	0.692	416
NL3V3 [87]	−16.24	0.148	269.60	34.43	81.97	−56.29	0.596	0.692	416
NL3V4 [87]	−16.24	0.148	269.60	33.98	76.87	−60.12	0.596	0.692	415
NL3V5 [87]	−16.24	0.148	269.60	33.12	68.15	−53.40	0.596	0.692	415
NL3V6 [87]	−16.24	0.148	269.60	32.35	61.05	−34.30	0.596	0.692	414
S271V1 [87]	−16.24	0.148	270.98	35.73	95.92	−44.06	0.700	0.771	416
S271V2 [87]	−16.24	0.148	270.98	35.05	86.87	−90.33	0.700	0.771	416
S271V3 [87]	−16.24	0.148	270.98	34.42	78.86	−120.99	0.700	0.771	416
S271V4 [87]	−16.24	0.148	270.98	33.82	71.75	−139.52	0.700	0.771	415
S271V5 [87]	−16.24	0.148	270.98	33.27	65.44	−148.63	0.700	0.771	415
S271V6 [87]	−16.24	0.148	270.98	32.74	59.81	−150.45	0.700	0.771	415
Z271S1 [87]	−16.24	0.148	270.95	34.95	86.86	−64.86	0.800	0.848	415
Z271S2 [87]	−16.24	0.148	270.95	34.07	76.62	−92.28	0.800	0.848	415
Z271S3 [87]	−16.24	0.148	270.95	33.27	67.81	−104.57	0.800	0.848	414
Z271S4 [87]	−16.24	0.148	270.95	32.53	60.18	−106.04	0.800	0.848	414
Z271S5 [87]	−16.24	0.148	270.95	31.84	53.57	−99.82	0.800	0.848	413
Z271S6 [87]	−16.24	0.148	270.95	31.20	47.80	−88.22	0.800	0.848	412
Z271V1 [87]	−16.24	0.148	270.95	35.34	90.86	−66.36	0.800	0.848	416
Z271V2 [87]	−16.24	0.148	270.95	34.80	83.61	−104.83	0.800	0.848	416
Z271V3 [87]	−16.24	0.148	270.95	34.54	80.23	−120.38	0.800	0.848	415
Z271V4 [87]	−16.24	0.148	270.95	34.28	76.99	−133.75	0.800	0.848	415
Z271V5 [87]	−16.24	0.148	270.95	34.04	73.90	−145.14	0.800	0.848	415
Z271V6 [87]	−16.24	0.148	270.95	33.80	70.94	−154.73	0.800	0.848	415
G1 [71]	−16.14	0.153	215.34	38.51	123.30	97.03	0.633	0.721	417
G2 [71]	−16.07	0.154	215.00	36.40	100.71	−7.48	0.664	0.744	416
G2* [81]	−16.07	0.154	216.87	30.46	69.87	−21.86	0.663	0.743	413
TM1* [88]	−16.33	0.145	281.13	36.87	101.72	−13.78	0.634	0.721	415
BSR1 [89]	−16.02	0.148	239.60	31.03	59.39	12.92	0.605	0.699	410
BSR2 [89]	−16.03	0.149	241.81	31.54	62.14	−2.87	0.605	0.699	410
BSR3 [89]	−16.09	0.150	232.84	32.81	70.63	−7.45	0.604	0.698	410
BSR4 [89]	−16.08	0.150	236.47	33.12	73.09	−20.92	0.607	0.700	412
BSR5 [89]	−16.12	0.151	237.33	34.51	83.51	−14.00	0.607	0.700	413
BSR6 [89]	−16.13	0.149	233.88	35.57	85.54	−49.59	0.602	0.697	414
BSR7 [89]	−16.18	0.149	229.76	37.19	98.93	−17.04	0.602	0.697	415
BSR8 [89]	−16.04	0.147	231.44	31.09	60.29	−0.68	0.606	0.699	410
BSR9 [89]	−16.08	0.147	230.70	31.57	63.76	−11.42	0.603	0.698	410
BSR10 [89]	−16.07	0.147	224.90	32.65	70.64	−16.62	0.601	0.696	410
BSR11 [89]	−16.08	0.147	227.98	33.73	78.89	−24.71	0.605	0.699	412
BSR12 [89]	−16.10	0.147	230.14	33.93	77.73	−44.28	0.608	0.701	414
BSR13 [89]	−16.13	0.147	227.25	35.77	90.94	−41.62	0.604	0.698	415
BSR14 [89]	−16.18	0.147	233.29	36.24	93.64	−41.83	0.609	0.702	415

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Table C1-continued from previous page

Model	E_0	ρ_0	K_0	J	L	K_{sym}	m_N^*/m_N	$m_{0,\Delta}^*/m_{0,\Delta}$	$\Lambda_{\pi N\Delta}$
BSR15 [89]	−16.03	0.146	229.14	31.04	61.96	−21.36	0.607	0.700	410
BSR16 [89]	−16.05	0.146	226.57	31.29	62.45	−24.16	0.607	0.700	410
BSR17 [89]	−16.05	0.146	219.62	31.92	67.28	−31.57	0.609	0.702	410
BSR18 [89]	−16.05	0.146	221.63	32.76	72.69	−42.25	0.606	0.700	412
BSR19 [89]	−16.08	0.147	222.06	33.83	79.58	−50.19	0.608	0.701	414
BSR20 [89]	−16.09	0.146	222.69	34.51	87.97	−39.86	0.606	0.700	415
BSR21 [89]	−16.12	0.145	219.47	35.92	92.86	−45.94	0.602	0.697	415
SVI-1 [90]	−16.30	0.149	261.34	36.94	116.12	95.11	0.617	0.708	417
SVI-2 [90]	−16.31	0.149	273.61	37.13	116.39	91.95	0.620	0.710	417
SIG-OM [91]	−16.31	0.149	262.58	36.91	111.62	40.96	0.623	0.713	417
NL$\rho\delta$A [29]	−16.00	0.160	240.16	30.71	102.67	127.37	0.750	0.809	410
NL$\rho\delta$B [29]	−16.30	0.148	271.55	34.06	138.90	398.27	0.600	0.695	410
Density-dependent models									
DD-ME2 [52]	−16.14	0.152	251.27	32.31	51.27	−87.22	0.572	0.674	410
DD-ME1 [92]	−16.23	0.152	243.84	33.06	55.43	−101.03	0.578	0.678	410
TW99 [93]	−16.25	0.153	240.16	32.76	55.31	−124.69	0.555	0.661	412
DD-F [94]	−16.04	0.147	222.87	31.62	55.97	−139.71	0.556	0.662	413
DD2 [95]	−16.03	0.149	242.41	31.67	55.03	−93.21	0.563	0.667	412
DD [96]	−16.02	0.149	239.88	31.64	55.97	−95.29	0.565	0.668	412
PKDD [79]	−16.27	0.150	261.94	36.79	90.20	−80.54	0.571	0.673	415
DDMEδ [30]	−16.08	0.152	219.59	32.34	52.80	−118.13	0.609	0.702	416
DDRH$\rho\delta$ [31]	−16.25	0.153	240.16	25.09	47.81	81.15	0.555	0.661	417
Point-coupling models									
FA3 [50]	−16.02	0.152	275.90	29.69	29.08	−275.05	0.676	0.753	430
FA4 [50]	−16.09	0.152	293.79	29.77	30.65	−257.83	0.680	0.756	430
FZ3 [50]	−15.93	0.152	297.75	29.96	33.78	−262.69	0.742	0.803	430
VZ3 [50]	−16.04	0.148	282.09	34.03	121.49	151.25	0.626	0.715	430
PC-F1 [51]	−16.18	0.151	255.20	37.78	117.15	74.68	0.610	0.703	430
PC-F3 [51]	−16.18	0.151	254.99	38.26	118.57	74.74	0.610	0.703	430

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