Accessing the in-medium effects on nucleon-nucleon elastic cross section with collective flows and nuclear stopping

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\textbf{A B S T R A C T}

A systematic study of the in-medium correction factor ($F$) on nucleon-nucleon elastic cross section is performed within the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model. The effects of the beam energy dependence of $F$ on the directed, elliptic flow and nuclear stopping in $^{197}$Au+$^{197}$Au collisions with energy ranging from 0.09 to 0.8 A GeV are explored. It is found that the directed, elliptic flow and nuclear stopping at relatively low energies are very sensitive to $F$, and the sensitivity gradually weakens with increasing beam energy. The beam energy dependent in-medium correction factor $F$ is deduced from the comparison of the excitation functions of the directed, elliptic flow and nuclear stopping between the calculated results and the FOPI experimental data.

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1. Introduction

The main goal of heavy-ion physics at intermediate energies is to explore the properties of the hot and dense strongly interacting nuclear matter. Comparing experimental data from terrestrial laboratories to theoretical calculations is one of the commonly used method to explore the fundamental properties of nuclear matter under a wide range of densities, temperatures, and isospin asymmetries [1–4]. Boltzmann-Vlasov-type (usually referred to BUU-type) and molecular dynamics-type (QMD-type) models are two of the most popular theoretical models for simulating heavy-ion collisions (HICs) at intermediate energies. The in-medium nucleon-nucleon elastic cross section (\textit{NNECS}) is one of the important ingredients of both models, and has been widely investigated in recent decades [5–8].

The \textit{NNECS} in free space $\sigma_{\text{el}}^{\text{free}}$ can be directly measured by experiments. However, the information of the in-medium \textit{NNECS} ($\sigma_{\text{el}}^{\text{in-med}}$) usually is constrained by theoretical assumptions. These theoretical calculations include, but not limited to, the Dirac-Brueckner approach with Bonn potential [9,10], the Dirac-Brueckner-Hartree-Fock approach with realistic nucleon-nucleon potential [11], the relativistic Brueckner-Hartree-Fock model [12,13], the closed time-path Green’s function approach [14]. It is shown definitely that the $\sigma_{\text{el}}^{\text{in-med}}$ is modified by the nuclear medium. However, the degree of this modification is still far from being solved thoroughly.

In most of theoretical models that used to simulate HICs at intermediate energies, the parameterized in-medium correction factor on \textit{NNECS} is commonly used for simplicity. In general, this correction factor $F = \sigma_{\text{el}}^{\text{in-med}} / \sigma_{\text{el}}^{\text{free}}$ is density- and/or momentum-, as well as isospin-dependent [15–21]. Many model simulations have demonstrated that various phenomena in HICs are sensitive to $\sigma_{\text{el}}^{\text{in-med}}$, thus the final state observables of HICs can be selected, such as the particle yields, collective flows and the nuclear stopping (energy dissipation), to extract the information of $\sigma_{\text{el}}^{\text{in-med}}$ [15–29]. In Ref. [30], a phenomenological formula for the in-medium \textit{NNECS} which depends on both density and beam energy was proposed, and found that the in-medium effect gradually weakens with increasing beam energy. By studying the nuclear stopping in central collisions in the Fermi-energy domain, it is also found a reduction on the in-medium effect, e.g., $F$ is about 0.2 at $E_{\text{lab}} = 0.035 A$ GeV and 0.5 at 0.1A GeV [27], respectively. Generally, the beam energy dependence of this reduction factor used in transport models is partly reflected in other physical quantities, such as in the density, momentum and/or simply in $\sigma_{\text{el}}^{\text{free}}$.

In our previous work, about twenty years ago, the in-medium \textit{NNECS} was studied based on the extended quantum hadrodynamics model in which the interaction between nucleons is described by exchanges of $\sigma$, $\omega$, $\pi$, $\rho$, and $\delta$ mesons [31,32]. Sev-
eral years later, the density-, momentum-, and isospin-dependent in-medium correction factor on NNECS was introduced into the ultra-relativistic quantum molecular dynamics (UrQMD) model [33, 34] in Ref. [35], and the transverse flow as a function of rapidity, the momentum quadrupole as a function of momentum, and the ratio of halfwidths of the transverse to that of longitudinal rapidity distribution were found to be sensitive to the in-medium correction factor. Later on, a reduction on $\sigma_{el}^{\text{in-med}}$ compared to $\sigma_{el}^{\text{free}}$ was deduced from the comparison of the nuclear stopping data at SIS energies [36], of the collective flows data at INRA energies [15,24,25]. However, a systematical deduction on $\sigma_{el}^{\text{in-med}}$ from both the nuclear stopping and collective flows data over INRA and SIS energies is still missing. The purpose of this work is to explore the beam energy dependence of the in-medium NNECS over a wide range of beam energy by using both the collective flows and nuclear stopping data. The simulations are performed on $^{197}$Au+$^{197}$Au collisions by the UrQMD model. This paper is organized as follows: in Sec. 2, the UrQMD model and the observables will be briefly recalled. In Sec. 3 the energy dependence of the in-medium NNECS and its influence on collective flows and nuclear stopping in HICs at SIS energies are shown. Finally the conclusions and outlooks are presented in Sec. 4.

2. The UrQMD model and observables

In the UrQMD model, each nucleon is represented by a coherent state of a Gaussian wave packet. And the coordinate $r_i$ and momentum $p_i$ of $i$-th nucleon are propagated according to Hamilton’s equation of motion [15] $\dot{r}_i = \frac{\partial H}{\partial p_i}$, $\dot{p}_i = -\frac{\partial H}{\partial r_i}$. Here, $(H)$ is the total Hamiltonian function of the system, comprising the kinetic energy and the potential energy. For studying HICs at intermediate energies, the following density- and momentum-dependent potential form is frequently used in QMD-like models [37,38],

$$V = \alpha \left( \frac{\rho}{\rho_0} \right) + \beta \left( \frac{\rho}{\rho_0} \right)^2 + \gamma_{\text{med}} \ln(1 + \alpha_{\text{med}}(\rho_0 - \rho)^2).$$

(1)

Where $\alpha = \text{393 MeV}$, $\beta = \text{320 MeV}$, $\gamma = \text{114.0}$, $\gamma_{\text{med}} = \text{157.0 MeV}$, and $\alpha_{\text{med}} = \text{500 } c^2/\text{GeV}^2$ are adopted in this work, which yields a soft and momentum-dependent equation of state with the incompressibility $K_0 = \text{200 MeV}$. It has been checked that varying $K_0$ within its presently accepted constraint (e.g., $K_0 = \text{200 }\sim \text{280 MeV}$) [1,3,39-43] will not affect significantly the results of present work discussed below. It is known that the Pauli blocking plays a vital role in theoretical study of HICs in the low to intermediate energies [6,15,26]. But different Pauli blocking algorithms are used in different transport models, and the effectiveness of these Pauli blocking algorithms differs substantially among the different transport model codes [6]. With the same treatments on mean fields and NN cross sections for the same combination system, the uncertainty of the $v_1$ slope from different transport codes, where different Pauli blocking algorithms exist, is about 13% (30%) at the beam energy 0.4 (0.1)A GeV [5]. By using three typical Pauli blocking algorithms (PB-Wigner (which is used in the current version of the UrQMD code), PB-Husimi, and PB-HSP), which are adopted in the different QMD-type models, the effects of different Pauli blocking algorithms on the excitation function of stopping power in HICs are analyzed. It is found that the uncertainties are less than 5% at beam energies below 0.3A GeV [26]. For simply, the Pauli blocking algorithm used in this work is set in the same way as our previous study [15], but the Pauli blocking algorithms used in transport models and its effect on observables certainly deserves further studies.

In the UrQMD model, the $\sigma_{el}^{\text{in-med}}$ is treated to be factorized as the product of a medium correction factor $F(\rho, p)$ and the cross sections in free space for which the experimental data are available,

$$\sigma_{el}^{\text{in-med}} = F(\rho, p) \cdot \sigma_{el}^{\text{free}}$$

(2)

with

$$F(\rho, p) = \left( f_0 + \frac{\lambda_{\text{NN}} - f_0}{1 + (p_{\text{NN}}/p_0)^\gamma} + f_0 \right).$$

(3)

where $f_0$, $\lambda$, $\gamma$, and $\rho_{\text{NN}}$ are the parameters and $\rho_{\text{NN}}$ is the momentum in the two-nucleon center-of-mass frame. In this work, the FU3FP2 and FU3FP4 parametrization of NNECS are adopted as we did in our previous works [15,24,44,45], and the parameter sets are listed in Table 1. Here, $f_0 > 1 (\sim 1)$ implies a possibly enhanced (reduced) in-medium effect on NNECS for $\rho_{\text{NN}} > 1$ GeV.

Based on our previous investigations, a stronger momentum reduction parametrization (FU3FP1) is used for reproducing experimental data at the Fermi energy region while the weaker FU3FP4 is used to extract the nuclear incompressibility and the density-dependent symmetry energy from the elliptic flow at higher energies. To better reflect the beam energy dependence of the in-medium correction on NNECS over a wide beam energy region, the factor $\text{tanh}(\text{El}_{\text{kin}}/\epsilon)$ is introduced into Eq. (3) so that

$$F(\rho, p) = \left( f_0 + \frac{\epsilon_{\text{NN}} - f_0}{1 + (p_{\text{NN}}/p_0)^\gamma} + f_0 \right).$$

(4)

Here, the parameter $\epsilon$ is set to be 0.2. This form is inspired by the in-medium correction factors used in pUUI model [18], and the momentum dependence of $F(\rho, p)$ [44]. The extended in-medium correction factors are labeled as $\epsilon$FU3FP2 and $\epsilon$FU3FP4. In addition, on the basis of our previous work [25], the fixed equivalent in-medium correction factors $F_{\text{el}} = \sigma_{el}^{\text{in-med}}/\sigma_{el}^{\text{free}}$ at different energies are further considered in this work.

In general, the directed, elliptic, and flow, and the nuclear stopping in HICs at intermediate energies are strongly related to the two-body scatters, and have been widely studied [2,15,28]. The directed ($v_1 = \left\langle \frac{p_0}{|p_0|+|p_2|} \right\rangle$) and elliptic ($v_2 = \frac{p_2 - p_1}{|p_2|+|p_1|}$) flow can be deduced from the Fourier expansion of the azimuthal distribution of detected particles [46]. The angle brackets indicate an average over all considered particles from all events. The nuclear stopping governs the amount of dissipated energy, i.e. the efficiency of converting the beam energy in the longitudinal direction into the transverse direction. Several different quantities of nuclear stopping have been used and investigated [47-51]. In order to compare with FOPI data, we mainly focus on varxz in the present work. It is defined as the ratio of the variances of particle rapidity distribution along the transverse $\Gamma^2(y_x)$ to those of the longitudinal $\Gamma^2(y_z)$ rapidity distribution [52], which read as $\text{varxz} = \frac{\Gamma^2(y_x)}{\Gamma^2(y_z)}$.

Here, $\text{varxz} = 1$ is corresponding to an isotropic thermal source, the energy distribution is isotropical. While $\text{varxz} > 1$, the energy is preferentially distributed along the beam direction [23,47,48].
3. Results

3.1. Collective flows

Fig. 1 shows the directed (top panels) and elliptic (bottom panels) flow of free protons in semi-central Au+Au collisions at \(E_{\text{lab}} = 0.15, 0.25, 0.44\) GeV, which are simulated with different in-medium correction factors on NNECS. The intervals of the reduced impact parameter \(b_0\) and the scaled transverse velocity \(u_0\) are chosen to be the same as in the FOPI analysis [53], i.e., \(0.25 < b_0 < 0.45\) and \(u_0 > 0.8\), respectively. These quantities are defined as \(y_0 = y_{/\text{y}_{\text{pro}}}\) with \(y_{\text{pro}}\) being the projectile rapidity in the center-of-mass system, \(b_0 = b/b_{\max}\) with \(b_{\max} = 1.15(A_1^{1/3} + A_2^{1/3})\) fm, \(u_0 = u_{/\text{u}_{\text{pro}}}\) with \(u_{\text{pro}}\) the transverse component of the four-velocity and \(u_{\text{pro}}\) is the velocity of the incident projectile in the center-of-mass system [53]. The results from calculations with FU3FP2, FU3FP4, \(\varepsilon\text{FU3FP2}\), and \(\varepsilon\text{FU3FP4}\) are represented by open up triangles, open down triangles, solid up triangles, and solid down triangles, respectively. A good agreement between the FOPI data and the model calculations in the whole rapidity range can be found. At 0.15 A GeV, \(v_1\) calculated with FU3FP2 and FU3FP4, i.e., without beam energy dependence of \(\sigma_{\text{in-med}}\) are slightly larger than that with \(\varepsilon\text{FU3FP2}\) and \(\varepsilon\text{FU3FP4}\), but these differences remain small at 0.25 and 0.44 GeV. For \(v_2\), the gaps between the calculations with \(\varepsilon\text{FUF}\) and FUF sets are visible and become gradually smaller with increasing beam energy, and finally almost unrecognizable at 0.44 GeV. These results imply that the collective flows are sensitive to the beam energy dependence of the in-medium NNECS, especially at relatively low energies.

In order to quantitatively show the influence of the beam energy dependence of the in-medium NNECS on the collective flows, the \(v_1\) slope and \(v_2\) at mid-rapidity for free protons are calculated and compared to the experimental data [53], and displayed in Fig. 2. As expected both \(v_{11}\) and \(v_{20}\) calculated with FUF and \(\varepsilon\text{FUF}\) sets are well separated at low beam energies, and the difference vanishes at high energies. It is known in our previous work [15,24,25,39,44], that a stronger reduction parametrization (e.g., FU3FP1) in \(\sigma_{\text{in-med}}\) is required to reproduce flow and stopping data at the Fermi energy, while a relatively weak reduction parametrization (e.g., FU3FP4) is favored at \(E_{\text{lab}} \geq 0.25\) A GeV. From Fig. 2, it can be seen that both \(v_{11}\) and \(v_{20}\) from 0.04 A GeV to 1.0 A GeV can be well reproduced with \(\varepsilon\text{FU3FP2}\).

It is of interest to quantitatively understand the in-medium effect on NNECS at different beam energies, the same as our previous work [25], \(v_{11}\) and \(v_{20}\) of free protons calculated with the fixed \(F\) at various energies are shown in Fig. 3. A fairly well linear relationship between the \(v_{11}\) (\(v_{20}\)) and \(F\) can be seen, confirming that the collective flows are indeed sensitive to the in-medium effects. Consequently, one can constrain the value of \(F\) at each beam energy with the chi-square analysis. The \(\chi^2 = \sum_{i} \frac{(X_{\text{th}} - X_{\text{exp}})^2}{\sigma_i^2}\) is plotted as a function of \(F\) in Fig. 4, where \(X_{\text{th}}\) and \(X_{\text{exp}}\) is the theoretical and the corresponding experimental values and \(\sigma_i\) is the theoretical error. There is also a well linear relationship between nuclear stopping and \(F\), however, the \(F\) constrained from nuclear stopping have a large error, since the precision of nuclear stopping data is much worse than that of collective flows. The obtained \(F\)
with a 2-σ confidence limit (at 95% confidence level) based on the comparison of the FOPI experimental data [53,54] on the collective flows of free protons with the UrQMD model calculations are shown in Table 2. One can find that this correction factor is beam energy-dependent, and by adopting the extracted F into simulations, the \(v_{11}\) and \(v_{20}\) data can be described fairly well, as shown in Fig. 2.

It is known that nucleon-nucleon collisions will be influenced by the nuclear medium, consequently the number of collisions will be affected by medium effects. The top panels (a1-a3) of Fig. 3 show the averaged collision number per nucleon experienced in central \(\text{Au}+\text{Au}\) collisions with different in-medium correction factors, the successful collision number and Pauli-blocked number are represented by orange and green bands, respectively. The total collision number from simulations with FU3FP2 and FU3FP4 is larger than that of εFU3FP2 and εFU3FP4. For example, the successful collision of FU3FP2 (FU3FP4) is about 42% (43%) larger than that of εFU3FP2 (εFU3FP4) at \(E_{\text{lab}} = 0.09 A\) GeV, while the collision number among different calculations at \(E_{\text{lab}} = 0.6 A\) GeV are almost the same. We have checked the relationship between the collision number and the equivalent in-medium correction factor \(F\), and found that with increasing the equivalent in-medium correction factor \(F\), i.e., decreasing the in-medium effects, the collision number will increase almost linearly. It must be emphasized again that the change of the equivalent fixed \(F\) results in a global effect, which gives a correction on all collisions, regardless of the density, momentum, and isospin. And at intermediate energies mentioned in this work, the values of \(v_{11}\) (\(v_{20}\)) will increase (decrease) when the collision number increases. Because nucleons which experience more collisions have larger probability to bounce-off and squeeze-out caused by the presence of the nearby spectator matter. The bottom panels (b1-b3) display the percentage of the successful (Pauli-blocked) collision number to total collisions number. These ratios hardly change when the in-medium correction factors are modified, since the Pauli blocking algorithm is not modified.

The time evolution of the \(v_{11}\) and \(v_{20}\) for free protons from semi-central \(\text{Au}+\text{Au}\) collisions at \(E_{\text{lab}} = 0.09 A\) GeV and \(0.4 A\) GeV are shown in Fig. 6. In panel (a), before \(\sim 50 \text{ fm/c}\) the value of \(v_{11}\) at 0.09 A GeV is negative, since the net contribution is attractive, which leads to the corresponding negative flow [57]. After \(\sim 50 \text{ fm/c}\), the final-state interactions still affect the collisions, and the contributions of two-body scatterings start to become stronger than those of the mean-field potentials. While, at 0.4 A GeV the net contribution is repulsive, leading to the positive flow. In panel (b), at low energies (0.09A GeV), the negative values for \(v_{20}\) can be seen at early time (compressed stage), then the compressed region expands but protons are preferential emitted in plane, reflecting positive values for \(v_{20}\) as result of the attractive potentials be-

![Image](image_url)
Fig. 7. Panels (a) and (b): the directed flow \( v_1 \) for free protons, deuterons, \( A=3 \) clusters and \(^4\text{He}\) as a function of transverse 4-velocities \( u_0 \) for semi-central \( \text{Au+Au} \) collisions at 0.25A GeV. Panels (c) and (d): the same as panels (a) and (b) but for the \( v_2 \) of free protons, deuterons, and tritons.

tween the nucleons. At higher energies (0.4A GeV), the strength of the collective expansion will overcome the rotational-like motion, leading to an increase of out-of-plane emission (negative elliptic flow).

In order to verify the effectiveness of the fixed equivalent in-medium correction factors \( F \), and \( \varepsilon \)FUFP2 in describing the FOPI experimental data [53], Fig. 7 shows the \( u_0 \) dependence of the \( v_1 \) [panels (a) and (b)] and the \( v_2 \) [panels (c) and (d)] of light charged particles in semi-central \( \text{Au+Au} \) collisions at 0.25A GeV as calculated with \( F = 0.8 \) and \( \varepsilon \)FUFP2. It is observed that both \( v_1 \) and \( v_2 \) can be reproduced fairly well, including the data of light mass fragments, such as the flows of \(^2\text{H}\) and \(^3\text{H}\) particles. However, the experimental data of \( v_1 \) of free protons and \(^4\text{He}\) particles cannot be well described when \( u_0 < 0.8 \), it might be due to the deficiency of \(^4\text{He}\) which is produced from heavier excited fragments and its instability after production in model simulations. Moreover, in QMD-like model, the yield of free nucleons is commonly overestimated while intermediate mass fragments are underestimated, due to simplifications in the initial wave function of particles and quantum effects in two-body collisions [24]. It implies that some of the free nucleons might belong to fragments. In addition, since the fragments flow effects are larger than that of free nucleons, the calculated free protons flows are consequently overestimated and the calculated fragments flows are underestimated.

3.2. Nuclear stopping

The nuclear stopping is closely related to the nucleon-nucleon collisions and in-medium effects [27,28]. Fig. 8 displays the nuclear stopping observable \( \text{varx}_z \) of free protons, deuterons, tritons, as well as hydrogen isotopes (\( Z = 1 \)) in central \( \text{Au+Au} \) collisions. In addition to the FUFP and \( \varepsilon \)FUFP sets, the fixed equivalent and energy-dependent factors \( F \), which are extracted from Fig. 3 and listed in Table 2, are taken into use as well. Again, it is found that the differences among the results calculated with \( \varepsilon \)FUFP and FUFP sets are well separated at lower energies but almost overlapped at higher energies. The FOPI data for \( \text{varx}_z \) of free protons, deuterons, tritons, as well as hydrogen isotopes can be fairly well reproduced with the calculations using the fixed equivalent factors (shown in Table 2 and Fig. 5). It means a consistent description on both the collective flow and nuclear stopping at beam energy below 0.8A GeV is achieved. At 0.8A GeV, \( \text{varx}_z \) calculated with different in-medium reduction factors on \( NN \) elastic collisions are close to each other, but overestimate the nuclear stopping.

3.3. Energy dependence of the reduction factors

As shown in Fig. 3, there is a fairly well linear relationship between the collective flows and the in-medium correction factors. By comparing the existing FOPI experimental data for proton flows [53,54] to the simulations with the UrQMD model, the fixed equivalent and energy-dependent in-medium correction factors \( F \) can be constrained from \( \chi^2 \) analysis, and is shown in Fig. 9, represented by olive solid circles. The red star symbols represent the results from INDIRA Collaboration [27]. The olive and orange bands represent the extracted fixed \( F \) within 2-\( \sigma \) and 1-\( \sigma \) uncertainty, respectively. The solid line represents nonlinear fits to the extracted \( F \) with 1-\( \sigma \) uncertainty with assuming \( F = a + b \cdot \tan(h) \) and the parameters can be found in Fig. 9. The pink band is 95% confidence intervals around the fitted lines. Let us finally mention that although the form of this energy-dependent in-medium correction factors is simple and rough, it provides intuitionistic and quantitative comprehension of in-medium effects on \( NN \) elastic collisions, and can be easily incorporated in transport model.

It is inevitable that at the higher energies studied in this work the \( NN \) inelastic scattering will occur, but its proportion is still not high [58,59]. For example, the rate for \( NN \rightarrow NN \) channels (where \( R \) denotes \( \Delta \) or \( N^* \) resonances) is about \( \sim 10\% \) while \( \sim 79\% \) for \( NN \rightarrow NN \) elastic collisions for \( \text{Au+Au} \) collisions at 0.8A GeV with \( F = 1.0 \). Indisputably, \( NN \rightarrow N\Delta \) will be influenced by nuclear medium, but the present considerations of in-medium effects on \( NN \rightarrow N\Delta \) cross section at intermediate energies are different.
To investigate the effect of in-medium NN inelastic section on collective flows and nuclear stopping, Au+Au collisions at $E_{lab} = 0.8$ AGeV with the incompressibility $K_0 = 200$ MeV, and the correction factor $F = 0.8$ for NNECS while $F_{inel} = \frac{\sigma_{in-med}}{\sigma_{inel}} \approx 0.5 \sim 3.0$ for NN inelastic cross section are performed. The same equivalent medium correction method as that for NN elastic is used here for the NN inelastic cross-section for simplicity. It is found that the values of $v_{11}$ and $varz$ increase slightly with the increase of $F_{inel}$, while $v_{20}$ keeps almost identical. This is because the enhanced NN cross section leads to a greater stopping [25,49,63]. Furthermore, the enhancement of the values of $v_{11}$ of protons and nuclear stopping $varz$ caused by the in-medium NN inelastic cross section is much weaker than that caused by in-medium NNECS, thus the in-medium correction factor $F$ on NNECS, extracted from the comparison of the experimental data with the calculated collective flows of protons, will be only slightly affected by the in-medium correction on NN inelastic cross section in the energy region studied in this work.

4. Summary and outlook

In summary, this work studies the energy dependence of the in-medium correction factor of NN elastic cross section, and its effects on the collective flows and nuclear stopping in 197 Au+197 Au collisions at beam energies from 0.9 to 0.8 AGeV with using the UrQMD model. By introducing the energy dependence into the parameterized in-medium correction factors (PUPF set) of NNECS, which depends on the density and the momentum, the experimental data of collective flows and nuclear stopping are compared with that from simulations with different in-medium correction factors. It is clearly seen that the energy dependence of the in-medium correction factor of NNECS has an obvious influence on collective flows and nuclear stopping in HICs at relatively low energies.

In addition, a fairly well linear relationship between the in-medium correction factor on NNECS and the collective flows is found. Then, the fixed equivalent and beam energy-dependent in-medium correction factors $F$ is extracted based on the comparison of the FOPI experimental data on the collective flows with the UrQMD model simulations. It is more exciting that the extracted $F$ is also consistent with previous results from INDRA Collaboration by using nuclear stopping as the probe [27]. The in-medium effects give a significant reduction of the NNECS, and this effect decreases with increasing beam energy ($\sim80\%$ at $E_{lab} = 0.044$ AGeV and $\sim24\%$ at 0.25 AGeV). Finally, a phenomenological formula for in-medium NNECS is presented by fitting the extracted $F$, and this formula can be easily incorporated in transport model. Additional calculations with other transport models by using the extracted $F$ will be useful for ascertaining the present results.

Although the influence of the nuclear incompressibility, Pauli-blocked algorithm and in-medium NN inelastic cross section on the extracted $F$ is insignificant separately, but there might be a coupling effect to some extent among these quantities, which may influence the extracted $F$ value somewhere visibly and deserve further studies, even with the help of the modern machine learning technique. In addition, a more consistent treatment of the medium effects on both nucleons, $\Delta$ baryons and $\pi$ mesons in a transport model is still urgently required in order to achieve a more systematic description on HICs at SIS energies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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