

# Nuclear in-medium effects on $\eta$ dynamics in proton–nucleus collisions

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**Abstract** The dynamics of the  $\eta$  meson produced in proton-induced nuclear reactions via the decay of  $N^*(1535)$  has been investigated within the Lanzhou quantum molecular dynamics transport model. The in-medium modifications of the  $\eta$  production in dense nuclear matter are included in the model, in which an attractive  $\eta$ -nucleon potential is implemented. The impact of the  $\eta$  optical potential on the  $\eta$  dynamics is investigated. It is found that the attractive potential leads to the reduction in high-momentum (kinetic energy) production from the spectra of momentum distributions and inclusive cross sections and increasing the reabsorption process by surrounding nucleons.

**Keywords** LQMD model ·  $\eta$  Production · In-medium effects · Proton–nucleus collisions

## 1 Introduction

The in-medium properties of hadrons are one of the topical issues in nuclear physics, in particular related to chiral symmetry restoration, phase transition from quark–gluon plasma to hadrons, nuclear equations of state (EoS), structure of neutron stars, etc. [1–3]. Theoretically, because of the asymptotic freedom of quantum chromodynamics (QCD), it is hard to directly obtain the in-medium properties of hadrons from QCD. Therefore, many effective field models have been used. Heavy-ion collisions in terrestrial laboratories provide a way to study the in-medium properties of hadrons in dense nuclear matter and to extract the high-density behavior of the nuclear symmetry energy (isospin asymmetric part of EoS) [4]. To understand the experimental data from heavy-ion collisions and hadron-induced reactions, microscopic transport models are necessary. The properties of hadrons in a nuclear medium are related to the issues of the interaction potential between the hadron and nucleon, in-medium corrections of cross sections on hadrons and resonance productions, reabsorption processes, etc.

The properties of  $\eta$  in the nuclear medium have been investigated by several approaches, such as the quark–meson coupling (QMC) model [5, 6], the chiral perturbation theory (ChPT) [7–9], the relativistic mean-field theory (RMF) [8], the chiral unitary approach [10]. Up until now, the strength of the  $\eta$  optical potential at normal nuclear density is not well refined, i.e., in the range from  $-20$  to  $-90$  MeV predicted by different models [9]. Measurements of  $\eta$  production in proton–nucleus collisions were taken in experiments [11, 12]. In this work, the dynamics of  $\eta$  in proton and heavy-ion-induced nuclear reactions are to be investigated within an isospin and momentum-

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dependent transport model (Lanzhou quantum molecular dynamics transport model) [13–15]. The impacts of the  $\eta$ -nucleon potential and symmetry energy on particle emission will be explored.

The article is organized as follows. In Sect. 2, we give a brief description of the LQMD model. The in-medium effects on  $\eta$  production are discussed in Sect. 3. Conclusions are summarized in Sect. 4.

## 2 Model description

It is well known that the wave function for each nucleon in the QMD-like models is represented by a Gaussian wave packet as follows [16]

$$\psi_i(\mathbf{r}, t) = \frac{1}{(2\pi L)^{3/4}} \exp\left[-\frac{[\mathbf{r} - \mathbf{r}_i(t)]^2}{4L}\right] \exp\left(\frac{i\mathbf{p}_i(t) \cdot \mathbf{r}}{\hbar}\right). \quad (1)$$

Here,  $\mathbf{r}_i(t)$  and  $\mathbf{p}_i(t)$  are the centers of the  $i$ th nucleon in the coordinate and momentum space, respectively. The  $L$  is the square of the Gaussian wave packet width, which depends on the mass number of the nucleus being in the form of  $L = (0.92 + 0.08A^{1/3})^2 \text{ fm}^2$  [17]. The total  $N$ -body wave function is assumed to be the direct product of the coherent states, where antisymmetrization is neglected. After performing a Wigner transformation for Eq. (1), we get the Wigner density as:

$$f(\mathbf{r}, \mathbf{p}, t) = \sum_i f_i(\mathbf{r}, \mathbf{p}, t) \quad (2)$$

with

$$f_i(\mathbf{r}, \mathbf{p}, t) = \frac{1}{(\pi\hbar)^3} \exp\left[-\frac{[\mathbf{r} - \mathbf{r}_i(t)]^2}{2L} - \frac{[\mathbf{p} - \mathbf{p}_i(t)]^2 \cdot 2L}{\hbar^2}\right]. \quad (3)$$

Then, the density distributions in the coordinate and momentum space are given by:

$$\rho(\mathbf{r}, t) = \sum_i \frac{1}{(2\pi L)^{3/2}} \exp\left[-\frac{[\mathbf{r} - \mathbf{r}_i(t)]^2}{2L}\right], \quad (4)$$

$$g(\mathbf{p}, t) = \sum_i \left(\frac{2L}{\pi\hbar^2}\right)^{3/2} \exp\left[-\frac{[\mathbf{p} - \mathbf{p}_i(t)]^2 \cdot 2L}{\hbar^2}\right], \quad (5)$$

respectively, where the sum runs over all nucleons in the reaction systems.

In the LQMD model, the dynamics of the resonances [ $\Delta(1232)$ ,  $N^*(1440)$ ,  $N^*(1535)$ ], hyperons ( $\Lambda$ ,  $\Sigma$ ,  $\Xi$ ,  $\Omega$ ), and mesons ( $\pi$ ,  $\eta$ ,  $K$ ,  $\bar{K}$ ) are described via hadron-hadron collisions, decays of resonances, mean-field potentials, and

corrections on threshold energies of elementary cross sections [14, 18]. The temporal evolutions of the baryons (nucleons and resonances) and mesons in the reaction system under the self-consistently generated mean-field are governed by Hamilton's equations of motion, which read as

$$\dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}, \quad \dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i}. \quad (6)$$

The Hamiltonian of baryons consists of the relativistic energy, the effective interaction potential, and the momentum-dependent part as follows:

$$H_B = \sum_i \sqrt{\mathbf{p}_i^2 + m_i^2} + U_{\text{int}} + U_{\text{mom}}. \quad (7)$$

Here, the  $\mathbf{p}_i$  and  $m_i$  represent the momentum and the mass of the baryons.

The effective interaction potential is composed of the Coulomb interaction and the local interaction potential

$$U_{\text{int}} = U_{\text{Coul}} + U_{\text{loc}}. \quad (8)$$

The Coulomb interaction potential is written as

$$U_{\text{Coul}} = \frac{1}{2} \sum_{i,j \neq i} \frac{e_i e_j}{r_{ij}} \text{erf}(r_{ij}/\sqrt{4L}), \quad (9)$$

where the  $e_j$  is the charge number, including protons and charged resonances.  $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$  is the relative distance between two charged particles.

The local interaction potential is derived from the Skyrme energy-density functional in the form of  $U_{\text{loc}} = \int V_{\text{loc}}(\rho(\mathbf{r})) d\mathbf{r}$ . The energy-density functional reads

$$V_{\text{loc}}(\rho) = \frac{\alpha}{2\rho_0} + \frac{\beta}{1+\gamma} \frac{\rho^{1+\gamma}}{\rho_0^\gamma} + E_{\text{sym}}^{\text{loc}}(\rho) \rho \delta^2 + \frac{g_{\text{sur}}}{2\rho_0} (\nabla \rho)^2 + \frac{g_{\text{sur}}^{\text{iso}}}{2\rho_0} [\nabla(\rho_n - \rho_p)]^2, \quad (10)$$

where the  $\rho_n$ ,  $\rho_p$ , and  $\rho = \rho_n + \rho_p$  are the neutron, proton, and total densities, respectively, and the  $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$  is the isospin asymmetry. The coefficients  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $g_{\text{sur}}$ ,  $g_{\text{sur}}^{\text{iso}}$ , and  $\rho_0$  are set to values of  $-215.7 \text{ MeV}$ ,  $142.4 \text{ MeV}$ ,  $1.322$ ,  $23 \text{ MeV fm}^2$ ,  $-2.7 \text{ MeV fm}^2$ , and  $0.16 \text{ fm}^{-3}$ , respectively. A Skyrme-type momentum-dependent potential is used in the LQMD model [13]

$$U_{\text{mom}} = \frac{1}{2\rho_0} \sum_{i,j \neq i} \sum_{\tau, \tau'} C_{\tau, \tau'} \delta_{\tau, \tau_i} \delta_{\tau', \tau_j} \int \int \int d\mathbf{p} d\mathbf{p}' d\mathbf{r} \times f_i(\mathbf{r}, \mathbf{p}, t) [\ln(\epsilon(\mathbf{p} - \mathbf{p}')^2 + 1)]^2 f_j(\mathbf{r}, \mathbf{p}', t). \quad (11)$$

Here,  $C_{\tau, \tau} = C_{\text{mom}}(1+x)$ ,  $C_{\tau, \tau'} = C_{\text{mom}}(1-x)$  ( $\tau \neq \tau'$ ), and the isospin symbols  $\tau(\tau')$  represent a proton or neutron.

The parameters  $C_{\text{mom}}$  and  $\epsilon$  were determined by fitting the real part of optical potential as a function of the incident energy from the proton–nucleus elastic scattering data. In the calculation, we take the values of 1.76 MeV and 500  $\text{c}^2/\text{GeV}^2$  for the  $C_{\text{mom}}$  and  $\epsilon$ , respectively, which result in the effective mass  $m^*/m = 0.75$  in the nuclear medium at a saturation density for symmetric nuclear matter. The parameter  $x$ , as the strength of the isospin splitting with a value of  $-0.65$ , is taken in this work, which leads to the mass splitting of  $m_n^* > m_p^*$  in the nuclear medium. A compression modulus of  $K = 230$  MeV for isospin symmetric nuclear matter is concluded in the LQMD model.

The Hamiltonian of the  $\eta$  meson is constructed as follows:

$$H_\eta = \sum_{i=1}^{N_\eta} \sqrt{m_\eta^2 + \mathbf{p}_i^2} + V_\eta^{\text{opt}}(\mathbf{p}_i, \rho_i). \quad (12)$$

The optical potential  $V_\eta^{\text{opt}}$  is

$$V_\eta^{\text{opt}} = \sqrt{(m_\eta^*)^2 + \mathbf{p}_i^2} - \sqrt{m_\eta^2 + \mathbf{p}_i^2}. \quad (13)$$

The effective mass of the  $\eta$  meson in the nuclear medium reads [8]

$$m_\eta^* = \sqrt{\left(m_\eta^2 - \frac{\Sigma_{\eta N}}{f_\pi^2} \rho_s\right) / \left(1 + \frac{\kappa}{f_\pi^2} \rho_s\right)}. \quad (14)$$

Here, the pion decay constant  $f_\pi = 92.4$  MeV,  $\Sigma_{\eta N} = 280$  MeV,  $\kappa = 0.4$  fm, the  $\eta$  mass  $m_\eta = 547$  MeV and  $\rho_s$  being the scalar nucleon density. The value of  $V_\eta^{\text{opt}} = -94$  MeV is obtained with zero momentum and saturation density,  $\rho = \rho_0$ . Shown in Fig. 1 is the optical potential as functions of momentum and baryon density, respectively. The strength of the potential increases with the baryon density, but decreases with the  $\eta$  momentum. It is shown that the potential will influence the  $\eta$  dynamics in dense nuclear matter.

The scattering in two-particle collisions is performed by using a Monte Carlo procedure, in which the probability to

be a channel in a collision is calculated by the contribution of the channel cross section to the total cross section. The primary products in nucleon–nucleon (NN) collisions are the resonances of  $\Delta(1232)$ ,  $N^*(1440)$ , and  $N^*(1535)$ . We have included the reaction channels as follows:

$$\begin{aligned} NN &\leftrightarrow N\Delta, \quad NN \leftrightarrow NN^*, \quad NN \leftrightarrow \Delta\Delta, \quad \Delta \leftrightarrow N\pi, \\ N^* &\leftrightarrow N\pi, \quad NN \leftrightarrow NN\pi(s\text{-state}), \\ N^*(1535) &\leftrightarrow N\eta \end{aligned} \quad (15)$$

The cross sections for  $N^*(1535)$  production can be estimated from the empirical  $\eta$  yields [19], such as  $\sigma(pp(nn) \rightarrow NN^*(1535)) \approx 2\sigma(pp(nn) \rightarrow pp(nn)\eta) =$  (a)  $0.34s_r/(0.253 + s_r^2)$ , (b)  $0.4s_r/(0.552 + s_r^2)$ , and (c)  $0.204s_r/(0.058 + s_r^2)$  in mb and  $s_r = \sqrt{s} - \sqrt{s_0}$  with  $\sqrt{s}$  being the invariant energy in GeV and  $\sqrt{s_0} = 2m_N + m_\eta = 2.424$  GeV [18]. Case (b) is used in this work. The  $np$  cross sections are about three times larger than that for  $nn$  or  $pp$ . We have taken a constant width of  $\Gamma = 150$  MeV for the  $N^*(1535)$  decay, and  $N^*(1535)$  has half probabilities decaying into the  $\eta$  meson and half to  $\pi$ .

### 3 Results and discussion

At the considered energies in this work, the  $\eta$  meson is produced from the decay of  $N^*(1535)$ . Therefore, the properties of  $N^*(1535)$  in nuclear medium are dominant on the  $\eta$  dynamics. We managed the mean-field potential for  $N^*(1535)$ , similarly to the nucleons.  $\pi^0$  and  $\eta$  have similar properties in the nuclear medium. Both of the mesons are neutral particles and decay from  $N^*(1535)$  with the same probability. In this work, we did not include the isospin, density, and momentum-dependent pion–nucleon potential in Ref. [18]. The  $\eta/\pi^0$  ratios in heavy-ion collisions are calculated as a test of our approach. The values in light ( $^{12}\text{C} + ^{12}\text{C}$ ), intermediate-mass ( $^{40}\text{Ar} + ^{40}\text{Ca}$ ,  $^{86}\text{Kr} + ^{90}\text{Zr}$ ), and heavy symmetric ( $^{197}\text{Au} + ^{197}\text{Au}$ ) systems are compared with the available data from the two-arm photon spectrometer (TAPS) collaboration [20], as shown in

**Fig. 1** The density and momentum dependence of the  $\eta$  optical potential

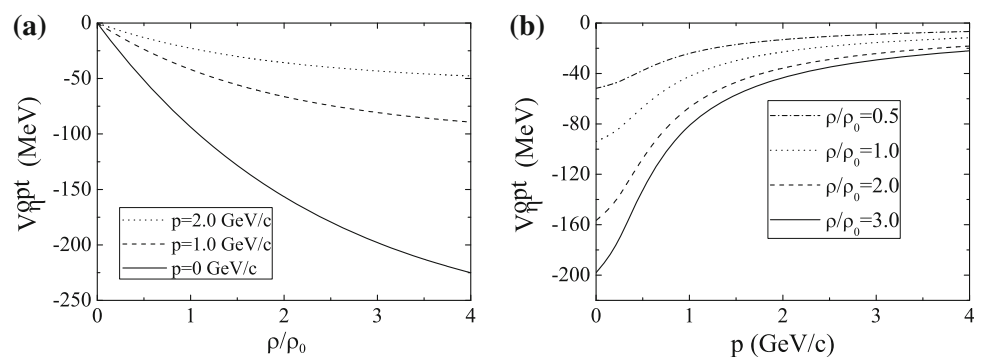


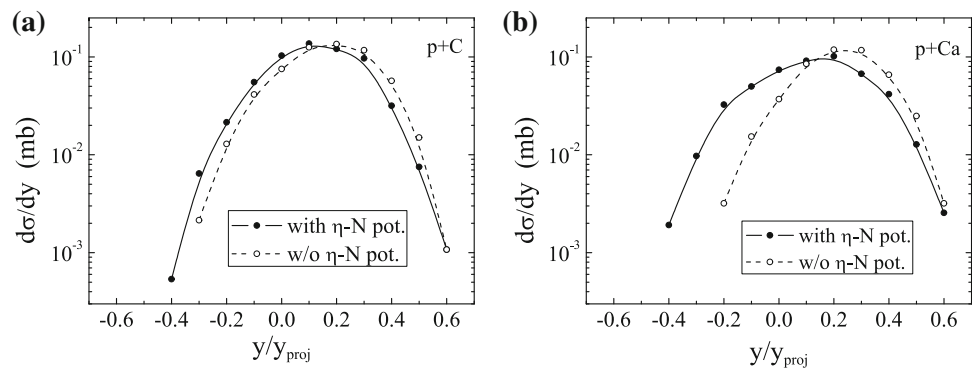
Table 1. Basically, the calculations are consistent with the available data. The ratios increase with participating numbers of colliding partners and incident energies.

**Table 1** Comparison of the  $\eta/\pi^0$  ratios of calculations and the available data [20]

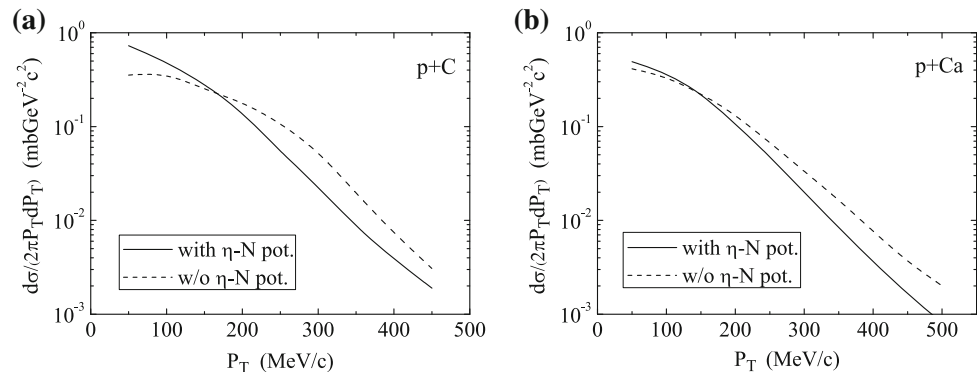
| $E_{\text{Beam}}(\text{A GeV})$ | Systems | Data (%)        | Calculated values (%) |
|---------------------------------|---------|-----------------|-----------------------|
| 1.0                             | C + C   | $0.57 \pm 0.14$ | 1.186                 |
| 1.0                             | Ar + Ca | $1.3 \pm 0.8$   | 1.321                 |
| 1.0                             | Kr + Zr | $1.3 \pm 0.6$   | 1.663                 |
| 1.0                             | Au + Au | $1.4 \pm 0.6$   | 2.087                 |
| 1.5                             | Ar + Ca | $2.2 \pm 0.4$   | 2.823                 |

The extraction of the in-medium properties of  $\eta$  in proton-induced reactions has advantages in comparison to heavy-ion collisions, in which particles are produced around the saturation densities ( $0.8\rho_0 \sim 1.2\rho_0$ ) [21–23]. The in-medium properties of  $\eta$  are related to the issues of resonance production in the nuclear medium, i.e.,  $N^*$  (1535), resonance-nucleon and  $\eta$ -nucleon potentials. Here, we concentrate on the  $\eta$ -nucleon interaction from proton–nucleus collisions and its impact on  $\eta$  production near threshold energies ( $E_{\text{th}}(\eta) = 1.26 \text{ GeV}$ ). Shown in Fig. 2 is the rapidity distributions in collisions of protons on  $^{12}\text{C}$  and  $^{40}\text{Ca}$  at the kinetic energy of 1.5 GeV. It should be noticed that the  $\eta$ -nucleon potential enhances the backward  $\eta$  emissions. The transverse momentum spectra are

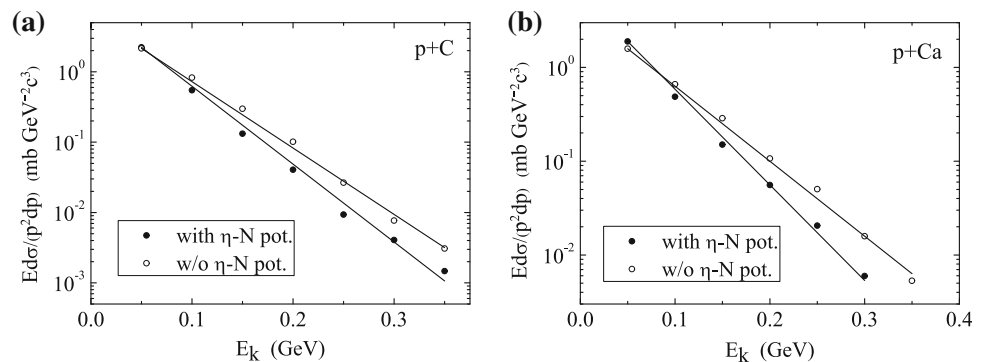
**Fig. 2** Rapidity distributions in proton-induced reactions at incident energy of 1.5 GeV. The solid and dashed lines are shown for guiding eyes



**Fig. 3** Transverse momentum distributions in proton-induced reactions at incident energy of 1.5 GeV



**Fig. 4** Kinetic-energy spectra of invariant cross sections in collisions of protons on  $^{12}\text{C}$  and  $^{40}\text{Ca}$  at incident energy of 1.5 GeV, respectively. The solid lines are shown for guiding eyes



calculated, as shown in Fig. 3. The high-momentum yields are reduced because of the enhancement of reabsorption process in  $\eta$ -nucleon scattering with the eta potential. Similar structure is also found from the kinetic-energy spectra of invariant cross sections, as shown in Fig. 4. The effect becomes more pronounced with increasing mass numbers of target nuclei because of larger collision probabilities between  $\eta$  and nucleons. The invariant spectra become steeper with the potential for both cases, which show a lower local temperature and longer interaction time of the  $\eta$  meson in the nuclear medium after inclusion of the  $\eta$ -nucleon potential. The strength of the  $\eta$ -nucleon potential is not well refined as of now, which is of significance in the formation of possible  $\eta$ -bound states ( $\eta$ -nucleus). The results would be helpful for extracting the  $\eta$ -nucleon potential from proton–nucleus collisions in the near future.

## 4 Conclusion

The dynamics of the  $\eta$  meson produced in proton-induced nuclear reactions have been investigated within the LQMD transport model. The  $\eta$  mesons are produced via the decay of  $N^*(1535)$ . The reabsorption of  $\eta$  and  $N^*(1535)$  by surrounding nucleons dominates the  $\eta$  distributions in phase space. The attractive  $\eta$ -nucleon potential enhances the reabsorption process in the nuclear medium, which leads to the reduction in forward emissions. The yields of  $\eta$  in collisions of protons on nuclei at high momenta (kinetic energies) are reduced with the  $\eta$ -nucleon potential. The effect becomes more pronounced by increasing the mass numbers of target nuclei.

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