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Kaon Dynamics in Heavy-ion Collisions at Intermediate Energies

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Abstract: Dynamics of kaons (K^0 and K^+) produced in nuclear reactions near threshold energies has been investigated within the Lanzhou quantum molecular dynamics (LQMD) transport model. The production yields are consistent with the available experimental data. A repulsive kaon-nucleon potential is implemented in the model through fitting the kinetic energy spectra of inclusive cross sections in heavy-ion collisions, which enhances the energetic kaon emission squeezed out in the reaction zone and reduces the total kaon yields. The comparison to the available data supports a soft equation of state in the density region of $2\sim3\rho_0$ for isospin symmetric nuclear matter. It is found that the stiffness of nuclear symmetry energy plays a significant role on the isospin ratio with decreasing the incident energy, in particularly in the domain of subthreshold energies.

Key words: LQMD model; kaon-nucleon potential; symmetry energy; K^0/K^+ ratio

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1 Introduction

Kaon production in relativistic heavy-ion collisions has been investigated as a useful tool to extract the information of the nuclear equation of state (EoS) in terrestrial laboratories. Kaons (K^0 and K^+) as a probe of EoS are produced in the high-density domain without subsequent reabsorption in nuclear medium[1]. The available experimental data already favored a soft EoS at high baryon densities[2–5]. The K^0/K^+ ratio was proposed as a sensitive probe to extract the high-density behavior of the nuclear symmetry energy (isospin asymmetric part of EoS)[6–8], which is poorly known up to now but has an important application in astrophysics, such as the structure of neutron star, the cooling of protoneutron stars, the nucleosynthesis during supernova explosion of massive stars etc[9]. Produced kaons in heavy-ion collisions can be easily deviated by surrounding nucleons in the dynamical evolutions. Consequently, the spectrum of the K^0/K^+ yields is to be modified and the constraint of the density dependence of symmetry energy from heavy-ion collisions is also influenced.

In this paper, kaon dynamics in heavy-ion collisions and extraction of EoS from kaon production are to be discussed with an isospin and momentum dependent transport model, *i.e.*, Lanzhou quantum molecular dynamics (LQMD) transport model. In which strangeness production is contributed from channels of baryon-baryon and pion-baryon collisions[5]. We have included the resonances ($\Delta(1232)$, N*(1440), N*(1535)), hyperons (Λ, Σ) and mesons (π, K, η, ρ, ω) in hadron-hadron collisions and the decays of resonances for treating heavy-ion collisions in the region of 1 *A*GeV energies. The momentum dependence of the symmetry potential was also implemented in the model, which results in an

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isospin splitting of proton and neutron effective mass in nuclear medium[10].

2 Model description

In the LQMD model, the time evolutions of the baryons (nucleons and resonances), hyperons and mesons in reaction system under a self-consistently generated mean-field are governed by Hamilton's equations of motion, which read as

$$\dot{\boldsymbol{p}}_i = -\frac{\partial H}{\partial \boldsymbol{r}_i}, \quad \dot{\boldsymbol{r}}_i = \frac{\partial H}{\partial \boldsymbol{p}_i} \ . \tag{1}$$

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

$$H_{\mathrm{B}} = \sum_i \sqrt{\boldsymbol{p}_i^2 + m_i^2} + U_{\mathrm{int}} + U_{\mathrm{mom}}. \tag{2}$$

Here the $\boldsymbol{p}_i$ 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 potential [10]. The local interaction potential is derived from the Skyrme energy-density functional as the form of $U_{\mathrm{loc}} = \int V_{\mathrm{loc}}(\rho(r))\mathrm{d}\boldsymbol{r}$. The energy-density functional reads

$$V_{\mathrm{loc}}(\rho) = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{1+\gamma}\frac{\rho^{1+\gamma}}{\rho_0^{\gamma}} + E_{\mathrm{sym}}^{\mathrm{loc}}(\rho)\rho\delta^2 + \frac{g_{\mathrm{sur}}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{\mathrm{sur}}^{\mathrm{iso}}}{2\rho_0}\left[\nabla(\rho_{\mathrm{n}} - \rho_{\mathrm{p}})\right]^2 \ , \tag{3}$$

where the ρ_{n}, ρ_{p} and $\rho = \rho_{\mathrm{n}} + \rho_{\mathrm{p}}$ are the neutron, proton and total densities, respectively, and the $\delta = (\rho_{\mathrm{n}} - \rho_{\mathrm{p}})/(\rho_{\mathrm{n}} + \rho_{\mathrm{p}})$ being the isospin asymmetry. The coefficients α, β, γ, g_{sur}, $g_{\mathrm{sur}}^{\mathrm{iso}}$ and ρ_0 are set to be the values of -215.7 MeV, 142.4 MeV, 1.322, 23 MeV fm^2, -2.7 MeV fm^2 and 0.16 fm^{-3}, respectively. A compression modulus of $K = 230$ MeV for isospin symmetric nuclear matter is produced with these parameters. A Skyrme-type momentum-dependent potential is used in the LQMD model[10]

$$U_{\mathrm{mom}} = \frac{1}{2\rho_0}\sum_{i,j,j\neq i}\sum_{\tau,\tau'} C_{\tau,\tau'}\delta_{\tau,\tau_i}\delta_{\tau',\tau_j}\iiint \mathrm{d}\boldsymbol{p}\mathrm{d}\boldsymbol{p}'\mathrm{d}\boldsymbol{r} \times f_i(\boldsymbol{r},\boldsymbol{p},t)\left[\ln(\epsilon(\boldsymbol{p}-\boldsymbol{p}')^2+1)\right]^2 f_j(\boldsymbol{r},\boldsymbol{p}',t) \ . \tag{4}$$

Here $C_{\tau,\tau} = C_{\mathrm{mom}}(1+x)$, $C_{\tau,\tau'} = C_{\mathrm{mom}}(1-x)$ $(\tau \neq \tau')$ and the isospin symbols $\tau(\tau')$ represent proton or neutron. The parameters C_{mom} and ϵ are determined by fitting the real part of optical potential as a function of incident energy from the proton-nucleus elastic scattering data. In the calculation, we take the values of 1.76 MeV, 500 c^2/GeV^2 for the C_{mom} and ϵ, respectively, which result in the effective mass $m^*/m = 0.75$ in nuclear medium at saturation density for symmetric nuclear matter. The parameter x as the strength of the isospin splitting with the value of -0.65 is taken in this work, which has the mass splitting of $m_{\mathrm{n}}^* > m_{\mathrm{p}}^*$ in nuclear medium. The symmetry energy is composed of three parts, namely the kinetic energy from fermionic motion, the local density-dependent interaction and the momentum-dependent potential as

$$E_{\mathrm{sym}}(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}\left(\frac{3}{2}\pi^2\rho\right)^{2/3} + E_{\mathrm{sym}}^{\mathrm{loc}}(\rho) + E_{\mathrm{sym}}^{\mathrm{mom}}(\rho) \ . \tag{5}$$

The local part is adjusted to mimic predictions of the symmetry energy calculated by microscopical or phenomenological many-body theories and has two-type forms as follows:

$$E_{\mathrm{sym}}^{\mathrm{loc}}(\rho) = \frac{1}{2}C_{\mathrm{sym}}\left(\frac{\rho}{\rho_0}\right)^{\gamma_{\mathrm{s}}} \ , \tag{6}$$

and

$$E_{\mathrm{sym}}^{\mathrm{loc}}(\rho) = a_{\mathrm{sym}}\left(\frac{\rho}{\rho_0}\right) + b_{\mathrm{sym}}\left(\frac{\rho}{\rho_0}\right)^2 \ . \tag{7}$$

The parameters C_{sym}, a_{sym} and b_{sym} are taken as the values of 52.5 MeV, 43 MeV, -16.75 MeV. The values of $\gamma_{\mathrm{s}} = 0.5$, 1.0, 2.0 have the soft, linear and hard symmetry energy with baryon density, respectively, and the Eq. (7) gives a supersoft symmetry energy, which cover the largely uncertain of nuclear symmetry energy, particularly at supra-saturation densities. All cases cross at saturation density with the value of 31.5 MeV. We chose two typical variations with baryon density, *i.e.*, hard and supersoft symmetry energies in the domain of high densities.

The hyperon mean-field potential is constructed on the basis of the light-quark counting rule. The self energies of hyperons are assumed to be two thirds of that experienced by nucleons. Thus, the in-medium dispersion relation reads

$$\omega(\boldsymbol{p}_i,\rho_i) = \sqrt{(m_{\mathrm{H}} + \Sigma_{\mathrm{S}}^{\mathrm{H}})^2 + \boldsymbol{p}_i^2} + \Sigma_{\mathrm{V}}^{\mathrm{H}} \tag{8}$$

with $\Sigma_S^H = 2\Sigma_S^N/3$ and $\Sigma_V^H = 2\Sigma_V^N/3$, which leads to the optical potential at the saturation density being the value of −32 MeV. The evolution of mesons (here mainly pions and kaons) is also determined by the Hamiltonian, which is given by

$$H_M = \sum_{i=1}^{N_M} \left(V_i^{\rm Coul} + \omega(\boldsymbol{p}_i, \rho_i) \right) \ . \tag{9}$$

Here the Coulomb interaction is given by

$$V_i^{\rm Coul} = \sum_{j=1}^{N_B} \frac{e_i e_j}{r_{ij}} \ , \tag{10}$$

where the N_M and N_B are the total numbers of mesons and baryons including charged resonances. We consider two scenarios for kaon (antikaon) propagation in nuclear medium, one with and one without medium modification. From the chiral Lagrangian the kaon and antikaon energy in the nuclear medium can be written as[2, 11]

$$\omega_K(\boldsymbol{p}_i, \rho_i) = \left[m_K^2 + \boldsymbol{p}_i^2 - a_K \rho_i^S + (b_K \rho_i)^2 \right]^{1/2} + b_K \rho_i, \tag{11}$$

$$\omega_{\bar{K}}(\boldsymbol{p}_i, \rho_i) = \left[m_{\bar{K}}^2 + \boldsymbol{p}_i^2 - a_{\bar{K}} \rho_i^S + (b_K \rho_i)^2 \right]^{1/2} - b_K \rho_i, \tag{12}$$

respectively. Here the $b_K = 3/(8 f_\pi^2) \approx 0.32$ GeV fm^3, the a_K and $a_{\bar{K}}$ are 0.18 GeV^2 fm^3 and 0.3 GeV^2 fm^3, respectively, which result in the strengths of repulsive kaon-nucleon (KN) potential and of attractive antikaon-nucleon potential with the values of 25.5 MeV and −96.8 MeV at saturation baryon density, respectively. Shown in Fig. 1 is the kaon and antikaon energy in the nuclear medium and the optical

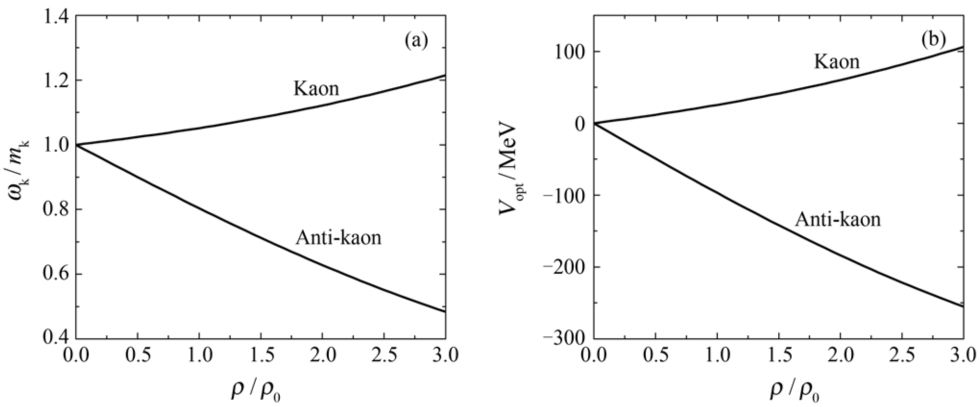

Fig. 1 Kaon energy in nuclear medium and optical potential as a function of baryon density.

potential computed from $V_{\rm opt} = \omega_{K,\bar{K}} - m_K$ at the momentum of $\boldsymbol{p} = 0$. The values of $m_K^*/m_K = 1.05$ and $m_{\bar{K}}^*/m_{\bar{K}} = 0.8$ at normal baryon density are concluded with the parameters. The effective mass is used to calculate the threshold energy for kaon and antikaon production, *e.g.*, kaon production in the pion-baryon collisions $\sqrt{s_{\rm th}} = m_Y^* + m_K^*$.

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 its contribution of the channel cross section to the total cross section. The primary products in nucleon-nucleon (NN) collisions in the region of 1 *A*GeV energies are the resonances of Δ(1 232), N*(1 440), N*(1 535) and the pions. We have included the reaction channels as follows:

$$\begin{aligned} &\mathrm{NN} \leftrightarrow \mathrm{N}\Delta, \quad \mathrm{NN} \leftrightarrow \mathrm{NN}^*, \quad \mathrm{NN} \leftrightarrow \Delta\Delta \ , \\ &\Delta \leftrightarrow \mathrm{N}\pi, \quad \mathrm{N}^* \leftrightarrow \mathrm{N}\pi, \quad \mathrm{NN} \leftrightarrow \mathrm{NN}\pi(\mathrm{s-state}) \ , \\ &\mathrm{N}^*(1535) \rightarrow \mathrm{N}\eta \ . \end{aligned} \tag{13}$$

At the considered energies, there are mostly Δ resonances which disintegrate into a π and a nucleon in the evolutions. However, the N* yet gives considerable contribution to the energetic pion yields. The energy and momentum-dependent decay widths are used in the model for the resonances of Δ(1 232) and N*(1 440)[12]. We have taken a constant width of $\Gamma = 150$ MeV for the N*(1 535) decay.

The strangeness is created by inelastic hadron-

hadron collisions as follows:

$$\mathrm{BB\to BYK,\ BB\to BBK\bar{K},\ B\pi\to YK,\ YK\to B\pi\ ,}$$
$$\mathrm{B\pi\to NK\bar{K},\ Y\pi\to B\bar{K},\ B\bar{K}\to Y\pi\ ,}$$
$$\mathrm{YN\to \bar{K}NN\ .} \tag{14}$$

Here the B, Y, K, $\bar{\mathrm{K}}$ stands for (N, △, N*), Y(Λ, Σ), K(K^0, K^+) and $\bar{\mathrm{K}}$($\overline{\mathrm{K}^0}$, K^-) respectively. The elastic scattering between strangeness and baryons are considered through the channels of KB→KB,YB→YB and $\bar{\mathrm{K}}\mathrm{B}\to\bar{\mathrm{K}}\mathrm{B}$. The charge-exchange reactions between the KN→KN and YN→YN channels are included by using the same cross sections with the elastic scattering, such as $\mathrm{K^0p\to K^+n}$, $\mathrm{K^+n\to K^0p}$ etc. Correction of effective mass of kaons in nuclear medium on the elementary cross section is considered through the threshold energy, which results in the reduction of kaon and the enhancement of anti-kaon yields in heavy-ion collisions. Shown in Fig. 2 is evolutions of pions, kaons and hyperons and the central baryon density produced in central ^{197}Au+^{197}Au collisions at incident energy of 1.5 *A*GeV. One can see that the pions and strange particles are mainly produced at supra-saturation densities ($\rho>\rho_0$). The observables can be probes to extract the high-density information of EoS. The pion yields saturate at time of the order of 30 fm/*c*, and the kaons are produced at early stage around 25 fm/*c*. The Bπ →YK contributes to be about 1/3 of the total kaon production, which retards the profile of the kaon yields in the calculations. The saturation of the hyperons is more slowly than the cases of pions and kaons owing to the exchange reactions $\mathrm{Y\pi\to N\bar{K}}$ and $\mathrm{N\bar{K}\to Y\pi}$.

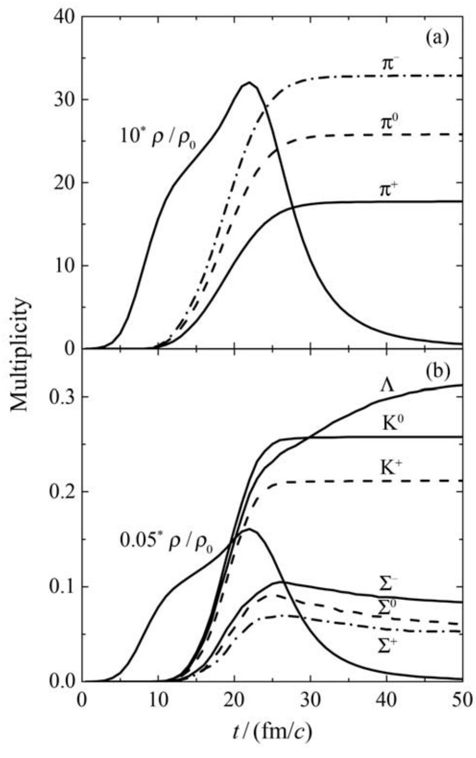

Fig. 2　Dynamical evolution of central density, pion and strangeness produced in the central collisions of ^{197}Au+^{197}Au at incident energy of 1.5 *A*GeV[5].

3　Results and discussions

The reliability of the calculations on the strangeness production can be checked from the available experimental data. Shown in Fig. 3 is the calculated excitation functions of strange particles for the heavy ^{197}Au+^{197}Au and the light ^{12}C+^{12}C reactions and compared with the KaoS data for the K^+ production[13]. The experimental data can be

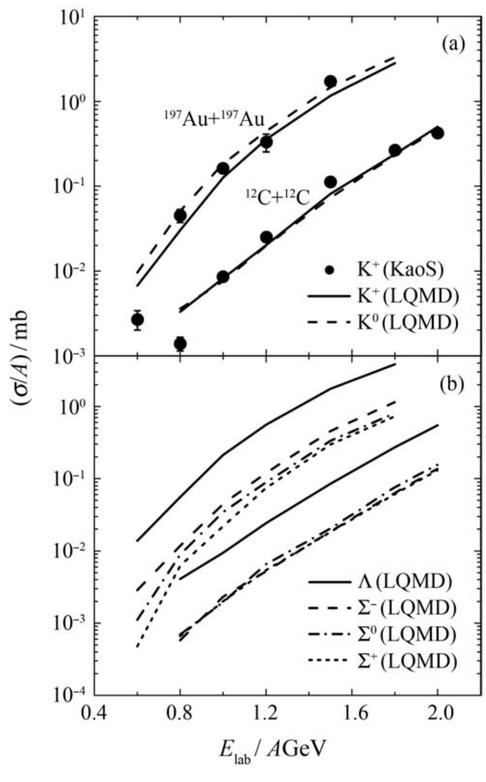

Fig. 3　Comparison of the calculated strangeness production cross section per mass number (σ/A) and the KaoS data for the K^+ production for the system ^{197}Au+^{197}Au and the reaction ^{12}C+^{12}C[5, 13].

well reproduced by calculations besides at very low threshold energies owing to the limited statistics. The larger cross sections of the strangeness production for heavier systems result from the larger region of the high-density phase diagram. The difference of production of the same isospin particles such as $K^{0,+}$ or $\Sigma^{-,0,+}$ is deviated from the isospin effects of collision systems.

To investigate kaon dynamics in momentum space and its correlation to the collision geometry and to the KN potential, the azimuthal anisotropy of kaon emission is presented from the transverse flow as shown in Fig. 4. The same trends with proton flows but with smaller values are found for the case without the KN potential. However, the repulsive potential even leads to the appearance of antiflows. The results are consistent with calculations in Ref. [14]. The Lorentz force of kaons in nuclear medium reduces the transverse flow and can well reproduce the FOPI data[14].

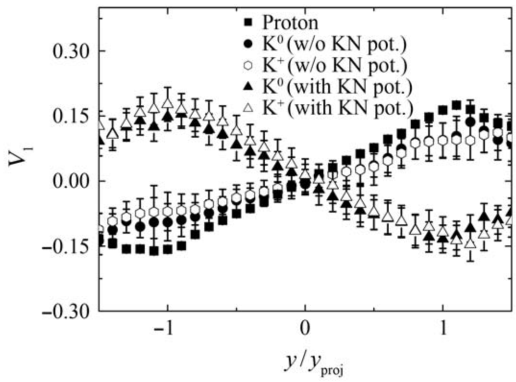

Fig. 4 Transverse flows of kaons produced in the ^{197}Au+^{197}Au reaction at the incident energy of 1.5 AGeV with and without the KN potentials as a function of the longitudinal rapidity. Proton flows are also implemented for a comparison.

To extract information of the high-density EoS, in Fig. 5 we show the kaon production in the ^{197}Au+^{197}Au and ^{12}C+^{12}C reactions for head-on collisions, normalized by the corresponding mass numbers and compared with the KaoS data[15]. The parameters α, β, γ in Eq. (3) are adjusted to get different modulus of incompressibility, but the saturation properties of nuclear matter has to be satisfied. A larger high-density region ($> \rho_0$) is formed in ^{197}Au+^{197}Au collisions and the compression depends on the nuclear equation of state. Whereas the compression in ^{12}C+^{12}C reaction is small and not sensitive to the stiffness of the EoS. The comparison to the available data supports a soft equation of state in the high-density region. Inclusion of the in-medium KN potential almost does not change the results.

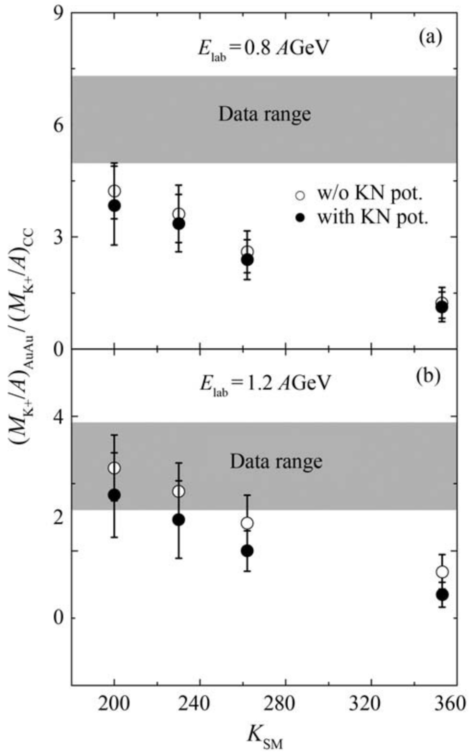

Fig. 5 Double ratios calculated within the LQMD model at 0.8 AGeV (a) and 1.2 AGeV (b) as a function of the incompressibility coefficient K_{SM} and compared with the available data for the K^+ production.

Kaons are produced at the early stage in heavy-ion collision and promptly emitted after production, which can get directly the information of high-density phase diagram[5]. Shown in Fig. 6 is the influence of the symmetry energy on the K^0/K^+ ratio produced in the ^{197}Au+^{197}Au reaction. It should be noted that the isospin effects appear at deep subthreshold energies. The in-medium potential slightly changes the K^0/K^+ value because of its influence on the kaon propagation and also on the charge-exchange reactions. One notices that a hard symmetry energy always has the larger values of the isospin ratios than the supersoft case in the domain of subthreshold energies ($E_{\rm th}$(K)=1.58 GeV). This is caused from the enhanced production of Δ^- resonances, *i.e.*, nn$\rightarrow$ pΔ^-, p$\Delta^- \rightarrow$ nΛK^0[8]. It should be noted that the threshold effect enlarges the isospin effect of the K^0/K^+ yields in the relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) calculations[6].

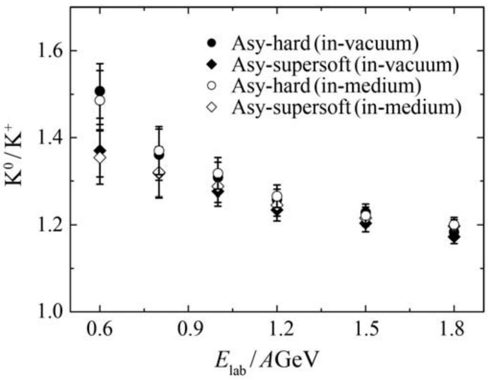

Fig. 6 Comparison of excitation functions of the K^0/K^+ yields for central ^{197}Au+^{197}Au collisions for the cases of hard and supersoft symmetry energies[8].

4 Summary

Kaon dynamics in heavy-ion collisions at near threshold energies has been investigated by using an isospin and momentum-dependent transport model (LQMD model). The kaon yields can be well reproduced with the model. The comparison to the available data supports a soft equation of state in the high-density region ($2 \sim 3\rho_0$). It is found that the K^0/K^+ ratio of neutron-rich heavy system in the domain of subthreshold energies is sensitive to the stiffness of nuclear symmetry energy, which is a promising probe to extract the high-density information of symmetry energy through comparison to experimental data. Precise measurements on subthreshold kaon production from neutron-rich nuclear collisions are still very necessary.

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中能重离子碰撞中K介子产生动力学研究

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摘要： 基于兰州量子分子动力学 (LQMD) 模型研究了阈能附近 K 介子 (K^0 和 K^+) 产生动力学机制。LQMD 模型能够较好地描述中能重离子碰撞中 K 介子产额分布。通过拟合 K 介子动能谱分布，计算中采用了排斥的 K-核子相互作用势。该光学势增强了高动量 K 介子产生，而降低了 K 介子总产额。结合实验数据比较，在高密区域给出了较软的对称核物质状态方程。对称能的软硬对 K^0/K^+ 比值起着重要作用，特别是在阈下区域。而 K 介子光学势对 K^0/K^+ 比值激发函数影响不明显。

关键词： 兰州量子分子动力学模型；K- 核子相互作用势；对称能；K^0/K^+

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