Kaon flow as a probe of the kaon potential in nuclear medium

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**Abstract**

The flow of kaons, i.e., the average kaon transverse momentum as a function of rapidity, and the associated flow parameter in heavy-ion collisions at SIS/GSI energies is investigated in the relativistic transport model. It is found that the pattern of kaon flow at the final stage is sensitive to the kaon potential used in the model and is thus a useful probe of the kaon potential in a nuclear medium.
Kaon properties in dense nuclear matter is a subject of considerable current interest. This knowledge is useful for our understanding of both chiral symmetry restoration in dense matter and the properties of the dense nuclear matter existing in neutron stars [1,2] and formed in heavy-ion collisions [3,4]. The possibility of $s$-wave kaon condensation in dense nuclear matter was first predicted by Kaplan and Nelson [5] based on the mean-field approximation to the chiral Lagrangian. Since then, there have been numerous studies on the properties of kaons in nuclear matter, based on various theoretical approaches such as the effective chiral Lagrangian [6–9], the Nambu–Jona-Lasinio (NJL) model [10], and the phenomenological off-shell meson-nucleon interaction [11]. The predictions from these models, however, have been inconsistent with each other, especially concerning the higher-order corrections beyond the mean-field approximation.

In the mean-field approximation to the effective SU(3)$_L \times$SU(3)$_R$ chiral Lagrangian [5,7], the kaon energy in a nuclear matter satisfies

$$\omega^2(k, \rho) = m_K^2 + k^2 - \frac{\Sigma_{KN}}{f_K^2} \rho_S + \frac{3}{4} \rho \frac{\rho}{f_K^2} \omega(k, \rho),$$

where $m_K$ and $k$ are the kaon mass (in free space) and momentum, respectively. The third term in the above equation is from the attractive scalar interaction due to chiral symmetry breaking and is determined by the kaon-nucleon sigma term $\Sigma_{KN} \approx 350 \text{ MeV}$, the nuclear scalar density $\rho_S$, and the kaon decay constant $f_K$, which is normally assumed to be the same as the pion decay width, i.e., $f_K \sim f_\pi \sim 93 \text{ MeV}$. The last term is from the repulsive vector interaction and is proportional to the nuclear density $\rho$. From Eq. (1), we obtain the kaon energy in a nuclear medium

$$\omega(k, \rho) = \left[ m_K^2 + k^2 - \frac{\Sigma_{KN}}{f_K^2} \rho_S + \frac{3}{8} \frac{\rho}{f_K^2} \right]^{1/2} + \frac{3}{8} \frac{\rho}{f_K^2}. \quad (2)$$

For low densities, including higher-order corrections beyond the mean-field approximation would lead to a kaon dispersion relation which is similar to that determined from the kaon-nucleon scattering length using the impulse approximation [12], i.e.,

$$\omega(k, \rho) = \left[ m_K^2 + k^2 - 4\pi(1 + \frac{m_K}{m_N})b_{KN}\rho \right]^{1/2}, \quad (3)$$
where $m_N$ is the nucleon mass and $\bar{a}_{KN} \approx -0.255$ fm is the isospin-averaged kaon-nucleon scattering length in free space [13].

However, theoretical calculations [14,15] indicate that the simple impulse approximation (Eq. (3)) underestimates experimental kaon-nucleus scattering data by 20-30%. A more repulsive kaon-nucleon interaction is needed to bring the theoretical results in better agreement with the experimental data [15]. In the Nambu–Jona-Lasinio model, higher-order corrections are found to cancel out almost completely the attractive scalar potential [10], so the kaon feels effectively only the repulsive vector potential. In this case, the kaon energy is

$$\omega(k, \rho) = \left[ m_K^2 + k^2 + \left( \frac{3}{8} \frac{\rho}{f_K^2} \right)^2 \right]^{1/2} + \frac{3}{8} \frac{\rho}{f_K^2}.$$  \hspace{1cm} (4)

In heavy-ion collisions, the dense matter formed is highly excited. Higher-order corrections are thus expected to be suppressed, and the mean-field approximation may be more appropriate. Indeed, for kaon production in heavy-ion collisions at energies below its production threshold from the nucleon-nucleon interaction in free space, it has been found [16] using the relativistic transport model [17] that an attractive kaon scalar potential is needed to explain quantitatively recent experimental data by the Kaos collaboration [18] from the heavy-ion synchrotron (SIS) at GSI. Neglecting the kaon scalar attraction would underestimate the kaon yield by about a factor of three.

Following Ref. [19], we define the kaon potential in a nuclear medium by

$$U(k, \rho) = \omega(k, \rho) - \omega_0(k),$$  \hspace{1cm} (5)

where $\omega_0 = (m_K^2 + k^2)^{1/2}$. The three potentials given by Eqs. (2), (3), (4) are all repulsive, as can be seen in Fig. 1 where the density dependence of the kaon potential at zero momentum is shown. The repulsion is relatively weak in the mean-field approximation (solid curve) because the repulsive vector potential is largely canceled by the attractive scalar potential. The kaon potential is strongly repulsive, if the scalar attraction is entirely canceled by higher-order corrections (dashed curve) as predicted in Ref. [10]. The result of the impulse approximation using the kaon-nucleon scattering length (dotted curve) lies between these two
extreme cases, which represent the lower and upper limits of current theoretical predictions for the kaon potential in a nuclear medium.

To probe the kaon potential in a dense matter, further experimental information will be very useful. In this Letter, we will show that the kaon flow in central heavy-ion collisions is sensitive to the kaon potential, and thus provides complementary, probably even more reliable, information on the kaon potential in a dense matter. Particle flows in heavy-ion collisions have been extensively studied in the past both experimentally [20,21] and theoretically [22,23]. The nucleon flow in both symmetric and asymmetric heavy-ion collisions has been used to determine separately the effects from the density and the momentum dependence of the nucleon potential [23]. Pion flow has also been investigated in the transport model [24,25], and it has been found to be in the same direction as the nucleon flow in central collisions but in the opposite direction in peripheral collisions as a result of the strong absorption of pions by nucleons. Recently, antiproton flow in heavy-ion collisions has been studied using the Relativistic Quantum Molecular Dynamics [26]. Because of the large annihilation cross section for antiprotons, the antiproton flow is found to be opposite to that of nucleons. Unlike pions and antiprotons, kaons are not seriously affected by stochastic two-body collisions as a result of their large mean free path. The flow of kaons is thus a relatively clean probe for the kaon potential in a nuclear medium.

Our study is based on the relativistic transport model developed in Ref. [17]. At incident energies around 1 GeV/nucleon as considered here, the colliding system consists mainly of nucleons, deltas and pions. While pions are treated as free particles, nucleons and deltas are propagated in their mean-field potentials generated by the attractive scalar and vector potentials as determined by the non-linear σ-ω model [27]. In the present work, we use the so-called soft equation-of-state with a nucleon effective mass of 0.83m_N and a compressibility of 200 MeV [28]. The Schrödinger-equivalent potential of this model is in fair agreement with that of the Dirac phenomenology when the nucleon kinetic energy is below 800 MeV. At higher energies, the explicit momentum dependence of the scalar and vector potentials is needed, and the parameterization recently proposed by the Giessen group would be more
appropriate [28].

Both elastic and inelastic reactions among nucleons, deltas and pions are included using the standard Cugnon parameterization [30] and the proper detailed-balance prescription [31]. Because of its small production probability, kaon production in heavy-ion collisions at subthreshold energies is treated perturbatively so that the collision dynamics is not affected by the presence of produced kaons [32]. The kaon production cross section and its momentum distribution from a baryon-baryon collision is taken from Ref. [33]. To improve the statistics for kaons, we have used the perturbative test particle method of Ref. [34].

Representing kaons by test particles, their motions are given by the following equations

$$\frac{dx}{dt} = \frac{k}{E^*}, \quad \frac{dk}{dt} = -\nabla_x U(k, \rho).$$ (6)

In the above, $U(k, \rho)$ is defined in Eq. (5) with $\omega(k, \rho)$ given by Eq. (2), (3), or (4), and corresponding $E^*$ given by $\omega(k, \rho) - (3/8)(\rho/f_K^2)$, $\omega(k, \rho)$, or $\omega(k, \rho) - (3/8)(\rho/f_K^2)$, depending on the assumptions made for the kaon potential.

The kaon-nucleon collision is included by using a kaon-nucleon total cross section of about 10 mb [35] which we take to be density-independent. After the collision the kaon direction is isotropically distributed as the kaon-nucleon interaction is mainly in the $s$-wave. Since kaon production is treated perturbatively, its effect on nucleon dynamics is neglected. The collision between a kaon and a pion via the $K^*$ resonance [36] has been neglected, as it is insignificant in heavy-ion collisions at 1 GeV/nucleon [16]. We have also included the Coulomb interactions of kaons with nucleons and pions.

We consider Au+Au collisions at an incident energy of 1 GeV/nucleon. In order to suppress the rescattering effects from the spectators, only the central collision at an impact parameter $b = 3$ fm will be studied. Our result for the nucleon flow is in reasonable agreement with preliminary data from the EOS collaboration [37] and with those from calculations based on the normal Vlasov-Uehling-Uhlenbeck model with a soft and momentum-dependent mean-field potential [23].

In Fig. 2 we show the average transverse momentum of kaons as a function of their center-
of-mass rapidity $y_{cm}$ at the final stage of the collisions. The open circles, corresponding to the case without the kaon potential, show that kaons flow in the same direction as nucleons, but with a smaller flow velocity. The results using a strong repulsive kaon potential, corresponding to Eq. (4), are shown by solid circles. The kaon flow in this case is in the opposite direction from that of nucleons, i.e., the appearance of an ‘antiflow’ of kaons with respect to nucleons. For a medium repulsion, as predicted by the impulse approximation (Eq. (3)), the kaon flow shown by the open squares in the midrapidity region is still opposite to the nucleon flow, but the ‘antiflow’ phenomenon is weakened. With a weak repulsion due to both the scalar and vector interactions, we find that the kaon flow shown by solid squares is in the same direction as that of the nucleons, but follows the nucleons less closely than in the case without the kaon potential. It is thus clear that the repulsive kaon potential tends to make kaons flow away from nucleons. How large the separation of kaons from nucleons is depends sensitively on the strength of the kaon potential. It is therefore possible to study the kaon potential in a nuclear medium by measuring the kaon flow in heavy-ion collisions.

To characterize the kaon flow more quantitatively, we introduce the flow parameter $F$ defined by the slope of $<p_x>$ at midrapidity, i.e., $F = d <p_x> / dy_{cm}|_{y_{cm}=0}$. The time evolution of the kaon flow parameter is shown in Fig. 3. Also shown in the figure by the dashed curve is the time evolution of the central baryon density $\rho/\rho_0$. In the early stage of the collision, there are very few kaons and a reliable determination of the flow parameter is not possible. We have therefore set it to zero until 8 fm/c. Kaons are mainly produced during the time interval from 5 fm/c to 15 fm/c when the system is compressed and baryon-baryon collisions are most energetic. During this period, kaons follow essentially the flow of nucleons, so the flow parameter is positive and similar to each other for the four cases considered here. The flow parameter reaches its maximum value around 15 fm/c when the compression almost ends. Afterwards the production of kaons is negligible and further changes of the flow parameter are mainly due to the kaon potential and kaon-nucleon scattering. In the expansion stage, clear differences are observed among the kaon flow parameters corresponding to different kaon potentials. Without the kaon potential, the final
kaon flow parameter ($\approx 52$ MeV) is slightly smaller than its maximum value as a result of kaon-nucleon scattering which are effectively repulsive and tend to slightly repel kaons away from nucleons. Including both scalar and vector potentials, the resulting kaon potential is weakly repulsive and the final flow parameter is still positive but is about a factor of 3 smaller than the case without the kaon potential ($\approx 17$ MeV). Using the kaon potential based on the impulse approximation which is more repulsive than the second case, the final flow parameter is negative and small ($\approx -9$ MeV); i.e., in the mid-rapidity region kaons flow in the opposite direction from the nucleons. Finally, if the scalar potential is fully canceled by higher-order corrections, which leads to a strong repulsive kaon potential, the kaon flow is negative and large ($\approx -86$ MeV). We would like to point out that the change of the kaon flow parameter occurs mainly in the expansion stage from 15 fm/c to 22 fm/c, when the central density is still above the normal nuclear matter density. Since the average density in the vicinity of kaons changes from about $2.6\rho_0$ to about $0.8\rho_0$, the kaon flow indeed probes the behavior of kaons in a dense nuclear matter.

The magnitude of kaon flow parameter depends also on the kaon-nucleon cross section. Increasing the cross section by a factor of two affects the kaon flow parameter by about 15 MeV for all cases of the kaon potential. This effect is comparable to the effect due to the difference between the kaon potential obtained from the impulse approximation using the scattering length and from the scalar and vector potentials derived from the mean-field approximation to the chiral Lagrangian. However, it is still much smaller than the difference between the cases with and without the kaon potential and the difference between the cases with and without the scalar potential. Thus the study of kaon flow is expected to provide useful information on the kaon potential in a dense matter.

In summary, using the relativistic transport model we have studied the kaon flow and the associated flow parameter in heavy-ion collisions at SIS/GSI energies. We have found that the kaon flow is essentially determined during the expansion stage of heavy-ion collisions. With different kaon potentials as predicted by current theoretical models, the pattern of kaon flow and the magnitude of the flow parameter have been investigated. Our results
indicate that the kaon flow is sensitive to the kaon potential. It is thus very useful in the future to carry out the flow analysis of the experimental kaon data from heavy-ion collisions in order to extract information on the kaon potential in a nuclear medium.

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Figure Captions

Fig. 1. Density dependence of the kaon potential in a nuclear medium.

Fig. 2. Average transverse momentum of kaons as a function of center-of-mass rapidity.

Fig. 3 Time evolution of the kaon flow parameter. Also shown by the dashed curve is the central baryon density.
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