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Antiflow of kaons in relativistic heavy ion collisions

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We compare relativistic transport model calculations to recent data on the sideward flow of neutral strange K_s^0 mesons for Au+Au collisions at 6*A* GeV. A soft nuclear equation of state is found to describe very well the positive proton flow data measured in the same experiment. In the absence of the kaon potential, the K^0 flow pattern is similar to that of protons. The kaon flow becomes negative if a repulsive kaon potential determined from the impulse approximation is introduced. However, this potential underestimates the data which exhibit larger antiflow. An excellent agreement with the data is obtained when a relativistic scalar-vector kaon potential, that has stronger density dependence, is used. We further find that the transverse momentum dependence of directed and elliptic flow is quite sensitive to the kaon potential in dense matter.

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The study of hadron properties in hot and dense medium created in a relativistic heavy ion collision is of considerable interest. Of particular importance is the in-medium modification of kaon properties as it is related to chiral symmetry restoration [1] and neutron star properties [2]. Since the work of Kaplan and Nelson [3] on the possibility of kaon condensation in dense matter, considerable effort has been devoted to the understanding of kaon properties in dense matter from heavy ion collisions [4–10]. All these investigations have lead to a general consensus that kaons feel a weak repulsive potential while antikaons feel a strong attractive potential [4]; the latter is responsible for K^- condensation in neutron stars. Since kaons are primarily produced at an early hot and dense stage in heavy ion collisions, a promising tool to search for kaon in-medium properties is via pressure-induced collective flow effects. The strength of the flow depends on the nuclear equation of state (EOS), the pressure gradient developed, and the kaon potential or dispersion relation in dense matter. Indeed, Li *et al.* [5], based on a relativistic transport model, have found that the repulsive kaon potential in nuclear medium tends to deflect kaons away from nucleons leading to an anticorrelated flow. On the other hand, antikaons were found [11] to have a similar flow as that of nucleons due to their attractive potential.

The theoretical predictions of exploiting the transverse flow to study the kaon self-energy in the medium have attracted much attention experimentally. The FOPI Collaboration at SIS/GSI has found [12–14] for the reaction Ni+Ni at $E_{\rm beam}=1.93A$ GeV a very small antiflow for kaon, i.e., the kaon average transverse momentum in the reaction plane as a function of rapidity is almost zero around midrapidity. The kaon sideward flow for this reaction, and especially for a heavier system Ru(1.69*A* GeV)+Ru, was found to be anticorrelated (correlated) with that of protons at low (high) transverse momenta. The azimuthal angular distributions of kaons measured by the KaoS Collaboration [15] in Au+Au collisions at 1*A* GeV indicate that kaons are emitted preferentially perpendicular to the reaction plane. Also a large K^- production cross section was observed by this group in Ni+Ni collisions at $E_{\rm beam}=(0.8-1.8)A$ GeV [16]. All these experimental findings at beam energies of $1-2\,A$ GeV clearly suggest the existence of an in-medium repulsive kaon-nucleon potential and a strong attractive antikaon-nucleon potential; the latter is also supported by K^- atomic data [17].

Flow analysis for K^+, K^-, and K_s^0 have been performed by several collaborations at AGS/BNL in Au+Au collisions at beam energies of $2-12\,A$ GeV [18,19]. Most of these experiments are confined to near-central collisions where nearly vanishing directed transverse kaon flow versus rapidity was observed. Several suggestions put forward about the origin of vanishing flow are, for example, isotropic production of kaons in hadron-hadron collisions [18]; that colliding hadrons have opposite rapidities [20]; cancellation between the negative flow at low transverse momenta and the positive flow at high transverse momenta [10].

Recently, the E895 Collaboration at AGS/BNL measured [21] the directed flow of neutral strange K_s^0 mesons in 6*A* GeV Au+Au collisions for central and midcentral events. The K_s^0 was found to have a considerable antiflow relative to that of the proton observed in the same experiment [22]. Using a relativistic transport model (ART) [23] for heavy ion collisions we investigate in this Rapid Communication if the appreciable kaon antiflow can be explained by the repulsive kaon potential in dense nuclear matter. We shall demonstrate that the typical relativistic scalar-vector mean field potential can indeed reproduce the data. We also predict that the flow anisotropies are sensitive to the kaon potential and thus are a useful probe of the EOS in high density matter.

In the ART model employed here, the nucleon mean field is parametrized by the usual Skyrme-type with a soft EOS corresponding to an incompressibility of $K=210$ MeV and a stiff EOS with $K=380$ MeV at normal nuclear matter density of $\rho_0=0.16$ fm^{-3}. In this model, the imaginary part of the kaon self-energy is approximately treated by kaon-hadron scatterings and its real part is given by the mean-field potential. The model has been used to study many aspects of heavy ion collisions at the AGS energies [10,24,25].

The ART model includes kaon production from baryon-baryon, meson-baryon, and meson-meson collisions. For the first two processes, the kaon production cross sections involving resonances are assumed to be the same as those for similar processes involving only nucleons and pions at the same center-of-mass energies. The kaon production cross section from the nucleon-nucleon and pion-nucleon collisions are then taken from the empirical data. For kaon production from meson-meson collisions, the cross sections involving only pion and rho mesons are taken from Ref. [26] based on a meson-exchange model, while those involving the omega meson are assumed to be similar to those involving the rho meson. Although the kaon momentum is fixed in both meson-baryon and meson-meson collisions, it has a distribution in baryon-baryon collisions and is obtained from the parametrization given by Randrup and Ko based on a modified phase space argument [27]. Since there is very little experimental information about the angular distribution of produced kaons in these elementary collisions, it is assumed in the ART model to be isotropic in the center-of-mass frame. Calculations using a forward-backward peaked angular distribution show little change in the final results. Also, kaon production in hadron-hadron scatterings is instantaneous in the original ART model. In the present study, we introduce a formation time of $\tau_{\rm fo}^K = 1.2$ fm/c.

Various approaches have been adopted to evaluate the kaon potential in dense matter [5,9]. In the present study, we shall use the two commonly used forms that have been quite successful in explaining several experimental data. One of these is based on the kaon dispersion relation determined from the kaon-nucleon scattering length using the impulse approximation:

$$w_K(\mathbf{p},\rho_b) = \left[m_K^2 + \mathbf{p}^2 - 4\pi\left(1+\frac{m_K}{m_N}\right)\overline{a}_{KN}\rho_b\right]^{1/2}, \qquad (1)$$

where m_K and m_N are the kaon and nucleon bare masses, ρ_b is the baryon density, and $\overline{a}_{KN} \approx -0.255$ fm is the isospin-averaged kaon-nucleon scattering length. The kaon potential in nuclear medium can then be defined as

$$U_K(\mathbf{p},\rho_b) = w_K(\mathbf{p},\rho_b) - (m_K^2 + \mathbf{p}^2)^{1/2}. \qquad (2)$$

This yields a repulsive potential of 30 MeV at ρ_0 for kaons at zero momentum. The other form of kaon potential used here is the scalar-vector potential determined from the chiral Lagrangian which can be written

$$w_K(\mathbf{p},\rho_b) = [m_K^2 + \mathbf{p}^2 - a_K\rho_S + (b_K\rho_b)^2]^{1/2} + b_K\rho_b, \qquad (3)$$

where $b_K = 3/(8f_\pi^2) \approx 0.333$ GeV fm^3, ρ_S is the scalar density. If only the Kaplan-Nelson term, which is related to the KN sigma term due to explicit chiral symmetry breaking, is considered, then the parameter a_K which determines the strength of the attractive kaon potential is $a_K = \Sigma_{KN}/f_\pi^2$. Since the exact value of Σ_{KN} and the magnitude of the higher order corrections are poorly known, we take a different approach where $a_K \approx 0.173$ GeV^2 fm^3 is determined by fitting the kaon repulsive potential of $U_K(\rho_0) = +30$ MeV as obtained in the impulse approximation.

Let us now make a systematic study of the directed flow of particles measured by the E895 Collaboration for the Au+Au collisions at $E_{\rm beam} = 6A$ GeV [21,22]. Before we confront the K_s^0 flow data, it is instructive to find out how far the ART model can describe the observed proton flow [22]. Calculations are performed for impact parameters $b = 5-7$ fm, since the events analyzed for the proton flow originate from this domain [22]. Figure 1 shows for protons the mean transverse momentum in the reaction plane $\langle p_x\rangle$ as a function of rapidity y (scaled to the beam rapidity). The data reveal a large proton flow with a slope of $F = d\langle p_x\rangle/d(y/y_{\rm c.m.}) \sim 180$ MeV/c at midrapidity. The ART model with a soft nuclear equation of state (solid line) provides a good agreement with the data over a large rapidity range. On the other hand, the stiff EOS (dashed line) results in a much stronger proton flow compared to the data. The enhanced pressure gradient for the stiff EOS provides a larger driving force for the expansion of the system and thereby a stronger collective flow. Henceforth, we restrict only to the soft nuclear EOS when comparing with the K_s^0 antiflow data measured in the same experiment.

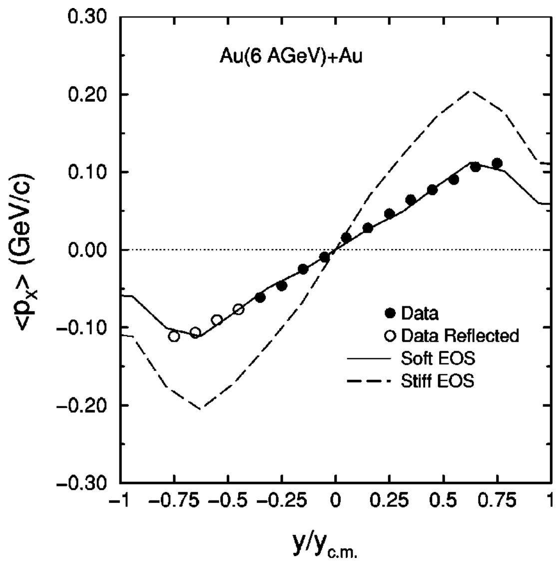

FIG. 1. The proton directed transverse flow $\langle p_x\rangle$ as a function of normalized rapidity $y/y_{\rm c.m.}$ in Au+Au collisions at $E_{\rm beam} = 6A$ GeV. The ART model calculations for a soft (solid line) and stiff (dashed line) nuclear EOS at an impact parameter $b = 5-7$ fm are compared with the E895 data (filled circles).

In Fig. 2, the ART model predictions of the sideward kaon flow as a function of rapidity are compared with the E895 data of K_s^0 mesons reconstructed from charged pion decays [21]. Since the antikaon $\overline{K}^0$ has a contribution of $\lesssim 10\%$ in the data sample at AGS energies, the observed K_s^0's are therefore primarily from neutral kaons K^0's. It is thus justified to study the collective flow of K^0 mesons in our model. In contrast to the protons, a pronounced in-plane antiflow for the K_s^0 is observed in the data with a slope of $F \simeq -127 \pm 20$ MeV/c. The K_s^0 flow data correspond to central and midcentral events with $b \lesssim 7$ fm and for transverse momentum $p_t \lesssim 700$ MeV/c [21]. We therefore restrict our calculations to these cutoff values. As is evident from Fig. 2, in the absence of kaon mean field, the K^0's have a flow pattern similar to that of the nucleons. This is not surprising as most of the K^0's are produced in the early compression

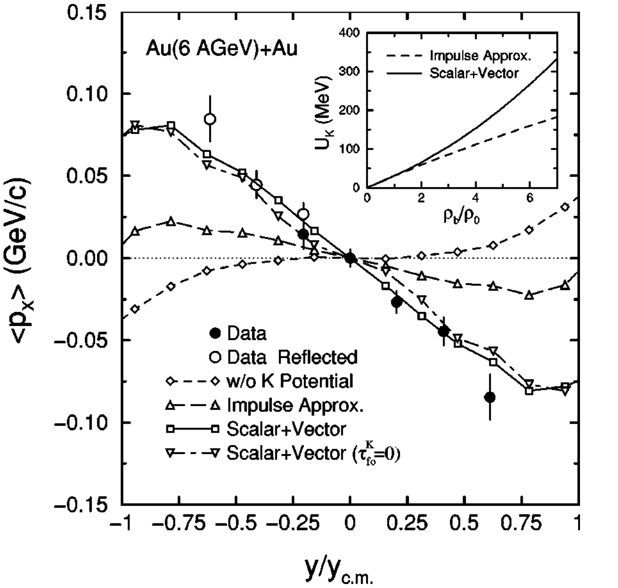

FIG. 2. The kaon directed transverse flow $\langle p_x \rangle$ as a function of normalized rapidity $y/y_{\mathrm{c.m.}}$ in Au+Au collisions at $E_{\mathrm{beam}} = 6A$ GeV. The filled circles are the E895 data while the other curves correspond to ART model calculations ($b \lesssim 7$ fm and $p_t \leqslant 700$ MeV/c) without kaon mean field potential and with kaon dispersion relations obtained from impulse approximation and scalar-vector potential. For the latter kaon potential, results with zero kaon formation time τ_{fo}^K are also shown. The inset shows the density dependence of the kaon potential U_K at zero momentum obtained in the impulse approximation and scalar-vector potential.

stage of the reaction at time $t \lesssim 5$ fm/c and the rescattering of the kaons with the nucleons in the dense matter thus causes them to flow in the direction of the nucleons.

We shall now demonstrate the effect of inclusion of kaon potentials on the K^0 flow. Using the kaon potential determined from the impulse approximation, the K^0's are repelled from the nucleons resulting in antiflow with respect to the nucleons (see Fig. 2). However, the $\langle p_x \rangle$ for kaons is found to underestimate the data as in Ref. [28]. In fact, theoretical calculations [29] have shown that the simple impulse approximation also underestimates experimental kaon-nucleus scattering data. The scalar-vector potential clearly has a stronger density dependence compared to the impulse approximation (see inset of Fig. 2) since the vector potential dominates over the scalar potential at densities above the normal nuclear matter value. The kaon flow predicted from the scalar-vector potential is found to have strikingly good agreement with the K_s^0 flow data as seen in Fig. 2. Although the final kaon flow is opposite to the proton flow, the primordial kaons flow with the nucleons up to the maximum compression stage of the collision, and their $\langle p_x \rangle$ values are nearly identical irrespective of the kaon potential employed. This stems from the fact that at the early stage of the collision the density gradient inside the participant matter is rather small and as a consequence the force acting on the kaon during its propagation is negligible. The potential (or baryonic density) gradient is substantial only during the expansion of the system so that the kaon potential could then

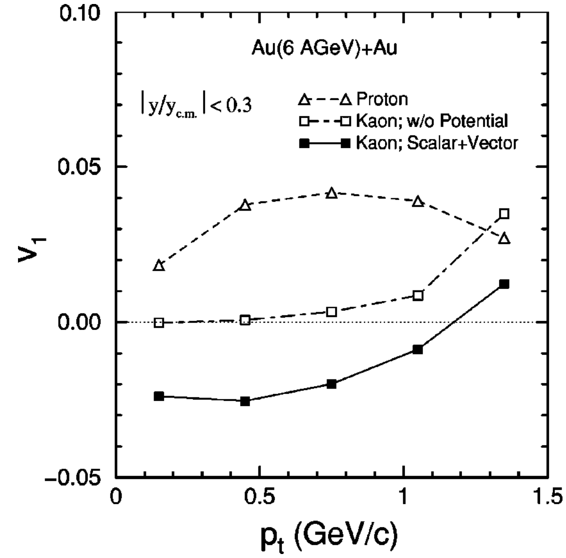

FIG. 3. The transverse momentum dependence of the directed flow v_1 for midrapidity protons and kaons without and with a kaon scalar-vector potential. The results are for Au($6A$ GeV)+Au collisions at an impact parameter of 6 fm.

effectively repel the K^0's away from the nucleons. This suggests that at the AGS energies, kaon flow may provide information about the kaon dispersion relation for densities below $\sim 4\rho_0$. Since the kaons produced in the ultradense stage mostly travel with nucleons, the kaon flow is expected to be sensitive to its formation time. This effect is illustrated in Fig. 2 for the scalar-vector potential where the kaon formation time τ_{fo}^K is set to zero. The early production of K^0 then leads to larger rescattering in the initial stage of the reaction. Consequently, the antiflow of K^0's is slightly suppressed especially near midrapidity. It is worth mentioning that the scalar-vector potential has been successful in reproducing several data at GSI energies of $1-2\,A$ GeV [9].

Additional insight into the origin of the transverse flow may be gained by considering the azimuthal angular distribution $dN/d\phi$ of the kaons at midrapidity by means of the Fourier expansion [30,31]

$$\frac{dN}{d\phi} = v_0[1 + 2v_1 \cos\phi + 2v_2 \cos(2\phi) + \cdots]. \qquad (4)$$

Here v_0 is the normalization constant, and the Fourier coefficients $v_1 = \langle \cos\phi \rangle = \langle p_x/p_t \rangle$ represent the directed flow and $v_2 = \langle \cos(2\phi) \rangle = \langle (p_x^2 - p_y^2)/p_t^2 \rangle$, referred to as the elliptic flow [32], reflects the azimuthal asymmetry of the emitted particles. While $v_2 > 0$ indicates in-plane enhancement, $v_2 < 0$ suggests a squeeze-out orthogonal to the reaction plane.

In Fig. 3 we depict the p_t dependence of v_1, dubbed as differential flow, for midrapidity K^0 ($|y/y_{\mathrm{c.m.}}| < 0.3$) without any kaon mean field and with the inclusion of scalar-vector kaon potentials. The results are for semicentral ($b = 6$ fm) Au+Au collisions at $6A$ GeV which can describe equally well the flow data. In the absence of a kaon potential, v_1 is found to be almost zero at low p_t but has a large positive value at high p_t. The low-p_t kaons are produced mostly in the relatively dilute region of the central expanding hadronic matter and are preferentially emitted in the antiflow direction away from the spectators. Consequently, they freeze out quite early in the reaction leading to a small in-plane flow. In contrast, kaons with large final p_t originate mainly inside the baryon-rich participant zone. These kaons are likely to suffer multiple rescatterings with the participant baryons and with the spectators. Hence the transverse momenta of these kaons are pushed to higher values with the final flow direction (and magnitude) similar to those of the nucleons. The differential flow for midrapidity nucleons seen here is similar to that observed experimentally [33].

In the presence of repulsive scalar-vector potential for K^0, the differential flow of kaons with $p_t \leqslant 1.2$ GeV/c becomes negative while kaons with higher p_t remains positive. The large negative v_1 for low-p_t kaons follows from the fact that these kaons are formed near the surface of the participant matter and thus feel a pronounced repulsive (kaon) potential gradient away from the baryons. Also the force acting on a kaon being inversely proportional to energy, the low energy kaons are strongly repelled from the baryons. Since the high-p_t kaons are produced deep inside the baryon-rich medium they are less repelled by the kaon potential both due to the smaller density gradient and eventually because of their larger energy. These kaons thus remain to flow in the same direction as the baryons. Note that the p_t cut in the E895 data for K_s^0 flow ($p_t \leqslant 0.7$ GeV/c) leads to enhanced antiflow for the K_s^0 than that when integrated over the entire p_t spectra.

In Au($6A$ GeV)+Au collisions the passage time of projectile and target spectator is given by $t \approx 2R/(\gamma v) \approx 6.4$ fm/c. During this time, the spectators prevent the participating hadrons from developing an in-plane flow. Therefore the hadronic matter is initially squeezed-out preferentially orthogonal to the reaction plane. The sign and magnitude of elliptic flow v_2, apart from the passage time, is also determined by the transverse expansion time of the participant matter. In the later stages of the reaction, however, the geometry of the participant region is such that in-plane emission is favored resulting in a positive v_2 [32,34]. Most of the kaons at the AGS energies are produced during the compression stage at times less than ~ 5 fm/c and thus would be shadowed by the spectators. Therefore kaons may serve as a sensitive probe to the EOS in the ultradense matter. Indeed, in peripheral and semicentral Au+Au collisions at $\sim 1A$ GeV, preferential emission of K^+ meson perpendicular to the reaction plane has been observed [15]. This may be interpreted as an evidence of repulsive kaon potential in the medium. [7]

In Fig. 4, the elliptic flow v_2 as a function of p_t is shown for protons and kaons using the same cuts as in Fig. 3. The proton v_2 gradually increases with p_t and has positive values even for small p_t. The low-p_t particles generally freeze out in the compression stage orthogonal to the reaction plane due to spectator shadowing, while the high-p_t particles undergo multiple rescattering. The experimental observation [35] for proton v_2 indicates a transition from squeeze-out to a preferential in-plane emission with increasing beam energies; the transition occurs at $E_{\rm beam} \sim 6A$ GeV. The ART model [25] and the UrQMD model [36] can describe the data consistently with a stiff nuclear EOS ($K = 380$ MeV); the v_2 for protons in the ART model is, however, insensitive to the EOS for $E_{\rm beam} \geqslant 6A$ GeV. This is in contrast to the prediction of Ref. [37] where a softening of the EOS with incident energy is deduced.

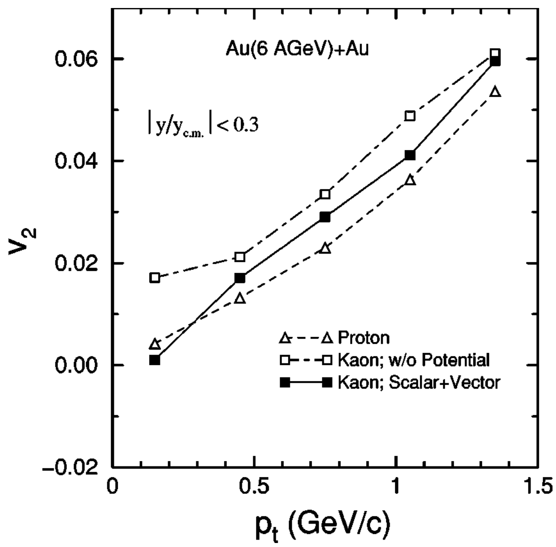

FIG. 4. Same as Fig. 3, but for the elliptic flow v_2.

The elliptic flow for K^0 in absence of any kaon potential is found to be slightly larger than that of the protons. This is caused by smaller shadowing by the spectators because of the time delay in their production and due to small $K-N$ total cross section of about 10 mb. With the inclusion of the scalar-vector potential, the v_2 for kaons is reduced. An explanation to this is as follows. The geometrical shape of the participant region at the initial stages entails a kaon repulsive potential gradient that is larger in the direction perpendicular to the reaction plane than parallel to the plane. Consequently, kaons in its mean field escape more freely perpendicular to the reaction plane. This effect is more pronounced for low-p_t kaons produced near the surface of the participant region. We however find that at the AGS energies considered here, the sensitivity of the squeeze-out to the kaon dispersion relation is smaller compared to that observed at GSI energies [6,7,15].

In summary, recent data on the sideward flow of neutral strange K_s^0 meson in $6A$ GeV Au+Au collisions have been compared to ART model calculations. The directed flow data for K_s^0 are opposite to that of protons and reveal a large antiflow. A soft nuclear EOS is found to reproduce very well the in-plane proton flow data at the same beam energy. We have used two different kaon dispersion relations: the impulse approximation where the mean field has a linear density dependence, and the typical relativistic scalar-vector potential. The K^0 mesons which flow with the nucleons in absence of a kaon mean-field potential exhibit an antiflow for the kaon potential derived from impulse approximation. However, the antiflow is found to underestimate the data. An overall good agreement with the data is achieved for the scalar-vector potential that has been equally successful in explaining the kaon data at SIS/GSI energies. Since the vector potential dominates at high densities, the scalar-vector potential becomes more repulsive than that in the impulse approximation. The K^0 flow at AGS energies is sensitive to the kaon potential at densities smaller than about four times the normal nuclear matter value as the kaon flow is essentially determined during the expansion stage of the collision. At higher densities reached at the early stages, the kaons generally flow with the nucleons and their flow magnitude is thus determined by the nuclear EOS. Kaons with small transverse momentum have a large negative differential flow due to stronger repulsion by the kaon potential, while positive kaon differential flow is a consequence of strong positive baryonic flow. In the semicentral collisions about midrapidity, the kaons are found to have an in-plane elliptic flow. The magnitude of this flow is slightly larger than that of the protons since the kaons suffer smaller shadowing. In the presence of the scalar-vector kaon potential, the kaon elliptic flow is decreased. This suggests that an analysis of directed flow in conjunction with elliptic flow of kaons may provide useful information on the kaon dispersion relation in dense matter.

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