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Antikaon flow in heavy-ion collisions: Effects of absorption and mean-field potential

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We study antikaon flow in heavy-ion collisions at SIS energies based on the relativistic transport model (RVUU 1.0). The production of antikaons from both baryon-baryon and pion-baryon collisions are included. Taking into account only elastic and inelastic collisions of the antikaon with nucleons and neglecting its mean-field potential as in the cascade model, a strong antiflow or anticorrelation of antikaons with respect to nucleons is seen as a result of the strong absorption of antikaons by nucleons. However, the antiflow of antikaons disappears after including also their propagation in the attractive mean-field potential. The experimental measurement of antikaon flow in heavy-ion collision will be very useful in shedding light on the relative importance of antikaon absorption versus its mean-field potential. [S0556-2813(96)51111-8]

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The collective flow of particles in heavy-ion collisions [1–6] has been proven to be a useful observable for studying both the nuclear equation of state at high densities and hadron properties in dense matter. Detailed analyses of proton flow in heavy-ion collisions using transport models have already shown that the experimental data are consistent with a soft nuclear equation of state if the momentum-dependence is properly included in the nuclear mean-field potential [7,8].

The flow of produced particles has also been extensively studied in transport models. For particles that are strongly absorbed by nucleons such as the pion, antikaon, and antiproton, studies based on the cascade model, in which their mean-field potentials are neglected, predict an appreciable antiflow or anticorrelation of these particles with respect to nucleons as a result of strong absorption by the spectator nucleons [9–13]. In particular, antikaon flow was studied in Ref. [12] for Au+Au collisions at AGS energies using the relativistic quantum molecular dynamics (RQMD) and was found to be anticorrelated with the nucleons. A similar calculation was carried out in Ref. [13] using a relativistic cascade (ARC) model. Again, the antikaon flow was found to be opposite to that of nucleons.

On the other hand, kaons and lambda hyperons, which cannot be absorbed by nucleons, are seen in cascade calculations to flow in the same direction as nucleons [3,13]. However, after including propagation in mean-field potentials, their flow patterns become very different [14–16]. Because of a weak repulsive potential resulting from the cancellation between an attractive scalar and a repulsive vector potential, kaons are ‘‘pushed’’ away from nucleons, leading to the disappearance of kaon flow in heavy-ion collisions, which has recently been confirmed by experimental data from Ni+Ni collisions at 1.93 GeV/nucleon measured by the FOPI collaboration at GSI [4]. On the other hand, the potential for a lambda in nuclear matter is known to be attractive so they are attracted towards nucleons, leading to a lambda flow almost as strong as that of nucleons [16]. This also seems to agree with the preliminary data from both the EOS [3] and the FOPI [4] collaboration.

The consistent and simultaneous explanation of the FOPI data on kaon and lambda flow in Ni+Ni collisions at 1.93 GeV/nucleon provide a strong evidence for the role of mean-field potentials in heavy-ion collisions. This is complementary to that provided by studies for the particle yields and spectra [17–20]. Therefore, it is important to see if the predicted antiflow of pions, antikaons, and antiprotons based on the cascade-type treatment is also affected by mean-field potentials.

For pion flow in heavy-ion collisions at SIS energies, the medium effect has recently been studied in Ref. [21] by introducing in the quantum molecular dynamics (QMD) an in-medium pion dispersion relation based on either the delta-hole model [22] or a phenomenological model [23]. The resulting attractive pion potential reduces the effect from pion absorption and thus changes significantly the pion flow pattern. The resultant pion flow could be in the same direction as nucleons if the attractive pion potential is sufficiently strong.

Recently, Brown and Rho [24] have shown via chiral Lagrangian with dropping pion decay constant in medium that the attractive scalar (before being cut down by the range term) and repulsive vector potentials acting on a kaon are just 1/3 of nucleon mean-field potentials in the Walecka model. For an antikaon, the vector potential becomes also attractive due to G parity. It is thus interesting to see if the resulting attractive antikaon mean-field potential has any effects on antikaon flow in heavy-ion collisions. In this Rapid Communication, we shall report the results from such a study.

To study medium effects in heavy-ion collisions at SIS energies, the relativistic transport model (RVUU 1.0) [25] has been extensively used by us in the past [14,17–20]. This model includes explicitly the nucleon, delta resonance, and pion. Furthermore, it can treat eta, kaon, antikaon, hyperon, antiproton, and dilepton production in heavy-ion collisions at SIS energies using the perturbative test particle method. The model is based on the nonlinear σ-ω model, but extended to include medium effects on the delta resonance, pion, and strange particles.

Medium modifications on kaon and antikaon are obtained from the mean-field approximation to the chiral Lagrangian, including the Brown and Rho scaling for the pion decay constant [15,24,26]. In this approximation, the antikaon dispersion relation in nuclear medium is modified by both attractive scalar and vector potentials, proportional, respectively, to the nuclear scalar ρ_S and baryon ρ_B densities [14], i.e.,

$$\omega(\mathbf{k},\rho_B)=\left[m_K^2+\mathbf{k}^2-\frac{\Sigma_{KN}}{f_\pi^{*2}}\rho_S+\left(\frac{3\rho_B}{8f_\pi^{*2}}\right)^2\right]^{1/2}-\frac{3\rho_B}{8f_\pi^{*2}}, \quad (1)$$

where $\Sigma_{KN}\approx 450$ MeV is the kaon-nucleon sigma term [27,28], and the in-medium pion decay constant f_π^* is related to that in free space $f_\pi\approx 93$ MeV by $f_\pi^{*2}/f_\pi^2\approx 0.6$ [15,24]. This scaling relation is derived from the Gell-Mann–Oakes–Renner relation and the Feynman-Hellmann theorem, and is supported by recent transport model analyses [31] of the CERES [29] and HELIOS-3 [30] dilepton data. In Eq. (1), we have neglected corrections to the scalar attraction from the range term as it is small for antikaon at high densities [15].

As in Ref. [14], we define the antikaon potential as

$$U(\mathbf{k},\rho_B)=\omega(\mathbf{k},\rho_B)-\omega_0(\mathbf{k}), \quad (2)$$

where $\omega_0(\mathbf{k})=(m_K^2+\mathbf{k}^2)^{1/2}$. At normal nuclear matter density ρ_0, the potential is about -190 MeV for a K^- at rest. This is very close to the -200 ± 20 MeV found in Ref. [32] from the kaonic atom data.

In addition to antikaon production from baryon-baryon collisions as considered in Ref. [18] using the cross section parameterized in Ref. [33], we also include in this study antikaon production from pion-baryon collisions. Experimental data are available for $\pi^-p\to pK^0K^-$, $\pi^-p\to nK^+K^-$, $\pi^-p\to nK^0\bar{K}^0$, and $\pi^+p\to pK^+\bar{K}^0$ [34]. Within experimental uncertainties, these data are more or less consistent with the charge-independent assumption and each can be reasonably fitted by the following parameterization:

$$\Sigma_{\pi^-p\to nK^+K^-}=\frac{0.08(\sqrt{s}-\sqrt{s_0})^2}{0.043+(\sqrt{s}-\sqrt{s_0})^2}\ \mathrm{mb}, \quad (3)$$

where $\sqrt{s}$ and $\sqrt{s_0}=m_N+2m_K$ are in units of GeV. The isospin-averaged cross section is then given by

$$\sigma_{\pi N\to NK\bar{K}}=\frac{7}{3}\sigma_{\pi^-p\to nK^+K^-}. \quad (4)$$

The isospin-averaged cross section for $\pi\Delta\to NK\bar{K}$ is assumed to be the same as that for $\pi N\to NK\bar{K}$. We find that for Ni+Ni collisions at 1.93 GeV/nucleon, the contributions to antikaon production from baryon-baryon and pion-baryon collisions are about 70% and 30%, respectively. As far as antikaon flow is concerned, the uncertainties in the elementary antikaon production cross sections do not play a significant role. However, it will be important in the future to carry out detailed analyses of these cross sections if one is interested in the absolute yield of antikaons from heavy-ion collisions.

We consider two scenarios for antikaon production and propagation in heavy-ion collisions. In the first scenario, we neglect possible medium modifications of the antikaon properties both in calculating its production and in treating its propagation in nuclear medium. In this cascade-type calculation, antikaons only undergo elastic and inelastic (mainly strange-exchange processes) collisions with baryons. The cross sections for the latter processes such as $\bar{K}N\to\bar{K}N$, $\bar{K}N\to\Lambda\pi$, and $\bar{K}N\to\Sigma\pi$ are taken from the parametrizations given in Ref. [35], which fit the experimental data quite well.

In the second scenario, we include the antikaon scalar and vector potentials in determining the threshold for its production. For antikaon production cross sections in baryon-baryon collisions, which are parameterized in terms of the maximum antikaon momentum $p_{\max}$, we evaluate its value using in-medium masses as in Ref. [18]. For antikaon production from meson-baryon interactions, we again use in-medium masses to calculate the threshold energy $\sqrt{s_0}$ in Eq. (3). This lowers the antikaon production threshold as the antikaon potential is attractive, leading to an enhanced production of antikaons as already demonstrated in Ref. [18]. In addition, we also include antikaon propagation in the mean-field potential to modify their momentum distribution. The equations of motion for an antikaon in nuclear medium are given by [14]

$$\frac{d\mathbf{r}}{dt}=\frac{\mathbf{k}}{E^*}, \quad \frac{d\mathbf{k}}{dt}=-\nabla_x U(\mathbf{k},\rho_B), \quad (5)$$

where $E^*=[m_K^2+\mathbf{k}^2-(\Sigma_{KN}/f_\pi^{*2})\rho_S+(3\rho_B/8f_\pi^{*2})^2]^{1/2}$.

In-plane flow is usually presented by the average transverse momentum $\langle p_x\rangle$ as a function of rapidity $y_{\mathrm{c.m.}}$ in the center-of-mass frame of the colliding nuclei. As a reference, we first show in Fig. 1(a) the nucleon flow in Ni+Ni collisions at 1.93 GeV/nucleon and impact parameter $b=4$ fm. The results for antikaon flow are shown in Fig. 1(b) by the dashed and the solid curve for the scenario without and with antikaon mean-field potential, respectively. In the cascade-type calculation, the antikaon flow is found to be in the opposite direction to that of nucleon, as was found in Refs. [12,13] for heavy-ion collisions at AGS energies. The flow parameter F, defined as the slope parameter at midrapidity, is found to be about -50 MeV. The appearance of antiflow of antikaons in heavy-ion collision in cascade calculation is due to the strong absorption of antikaons in the direction of nucleon flow.

Including antikaon propagation in the mean-field potential, the picture changes dramatically. Because of an attractive potential, antikaons are ''pulled'' towards nucleons, as was found for the lambda hyperon [16] and pion [21], both feeling attractive potentials in nuclear medium. The effect from antikaon propagation in mean-field potential is seen to be stronger than the effect from its absorption by nucleons, and the final antikaon flow turns out to be quite weak with a flow parameter of about 15 MeV.

The effects of absorption and mean-field potential on antikaons can also be studied from their azimuthal distribution. As shown in Ref. [36], this effect can be most clearly seen near the target and projectile rapidities, due to the large anisotropy in the nucleon azimuthal distribution. For comparisons, we show in Fig. 2(a) the nucleon azimuthal distribution $dN/d\phi$ near the target rapidity. A significant excess of nucleons is seen in the lower hemisphere near the target. As shown in Ref. [36], a similar excess of nucleons appears also

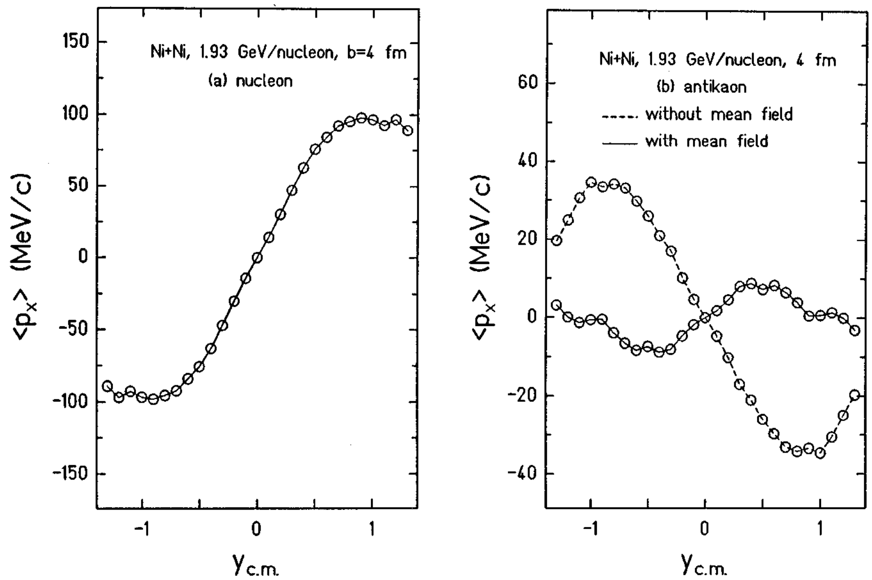

FIG. 1. Nucleon (a) and antikaon (b) flow in Ni+Ni collisions at 1.93 GeV/nucleon and impact parameter $b=4$ fm.

in the upper hemisphere near the projectile rapidity. On the other hand, the nucleon distribution is almost isotropic near midrapidity.

The antikaon azimuthal distribution near the target rapidity is also shown in Fig. 2. Fig. 2(b) gives the distribution of primordial antikaons that do not suffer any final-state interactions. The distribution is more or less isotropic, as was also found in Ref. [12] for primordial antiprotons. The distribution of antikaons including the absorption effect but not the mean-field effect is shown in Fig. 2(c). The dip near $\phi=180°$ shows that there is a strong anticorrelation of antikaons with nucleons as a result of the absorption of antikaons by the spectator nucleons, which are located in the lower hemisphere. This has also been observed in Ref. [12] for antiprotons in heavy-ion collisions at AGS energies. Figure 2(d) shows the azimuthal distribution of antikaons including both absorption and mean-field effects. As in the case of in-plane flow, the effect from the mean-field potential is stronger than that from absorption, and the final antikaon azimuthal distribution turns out to be almost isotropic. Although not shown here, similar effects on antikaon azimuthal distribution are again seen near the project rapidity.

In summary, using the relativistic transport model (RVUU 1.0), we have studied both the antikaon in-plane and out-of-plane flow in heavy-ion collisions at SIS energies. In particular the effects of antikaon absorption and mean-field potential on the flow pattern are investigated. In the cascade-type treatment, we observe clearly the anticorrelation of antikaons with respect to nucleons, as was seen in both the RQMD and

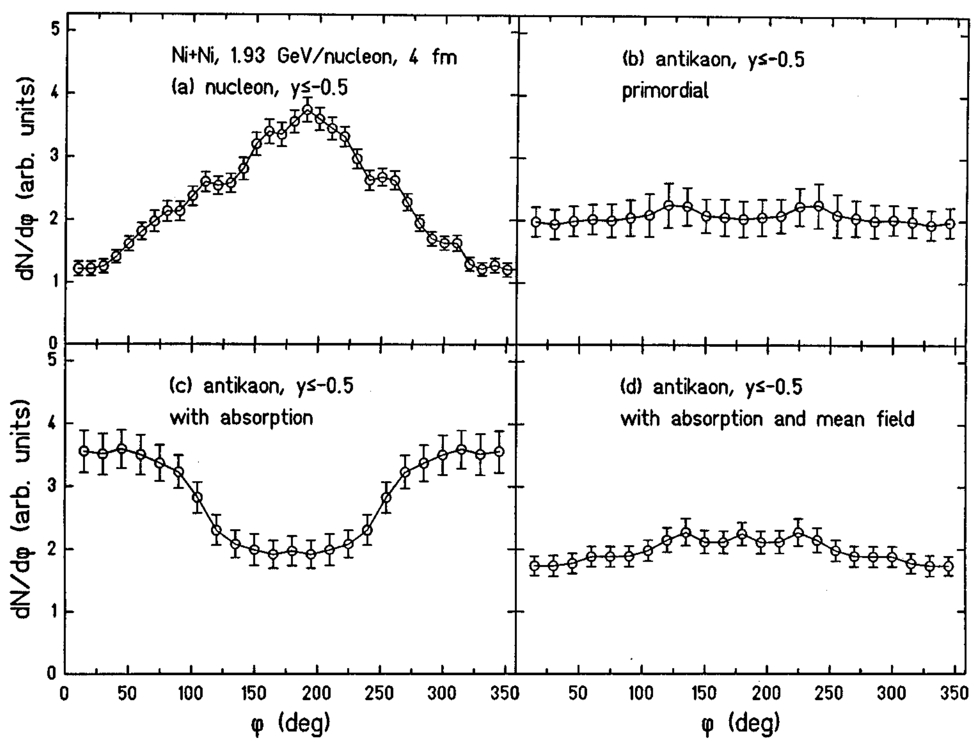

FIG. 2. Nucleon (a) and antikaon (b–d) azimuthal distributions near target rapidity for the reaction in Fig. 1.

ARC calculations [12,13]. This is mainly due to the strong absorption of antikaons by nucleons. If we further include the propagation of antikaons in the attractive mean-field potential, the strong anticorrelation between antikaons and protons seen in both in- and out-of-plane flow disappears, and the antikaon distribution becomes almost isotropic. Since there is little doubt that antikaons are strongly absorbed by nucleons, the experimental observation of a disappearance of antikaon flow will provide a strong evidence for the presence of antikaon mean-field potential in medium. Similar considerations can be applied to antiprotons, and such a study will be reported elsewhere.

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