Enhanced Out-of-Plane Emission of K^+ Mesons Observed in Au + Au Collisions at 1A GeV

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The azimuthal angular distribution of K^+ mesons has been measured in Au + Au collisions at 1A GeV. In peripheral and semicentral collisions, K^+ mesons are emitted preferentially perpendicular to the reaction plane. The strength of the azimuthal anisotropy of K^+ emission is comparable to the one of pions. No in-plane flow was found for K^+ mesons near projectile and target rapidity. [S0031-9007(98)06942-7]

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Relativistic nucleus-nucleus collisions provide the unique possibility to study both the behavior of nuclear matter at high densities and the properties of hadrons in the dense medium. In particular, the production and propagation of strange mesons is considered to be sensitive to in-medium effects. Theory predicts kaon-nucleon potentials in nuclear matter which are repulsive for K^+ but attractive for K^- mesons [1–3]. The large K^- production cross section found in Ni + Ni collisions [4,5] has been regarded as evidence for a reduced effective mass of the K^- meson in nuclear matter [6,7].

The K^+ mesons are expected to be repelled from the nucleons and hence the kaon emission pattern should be anticorrelated with the collective motion of the nucleons. Indirect evidence for such a behavior comes from a measurement of the average K^+ momentum in the event plane in Ni + Ni collisions at 1.93A GeV: the directed in-plane flow found for protons and lambdas near target rapidity is absent for kaons [8]. This finding was attributed to a repulsive K^+N potential which compensates the effect of the directed nucleon flow [9].

At midrapidity the directed flow of nuclear matter vanishes for symmetry reasons and the protons, neutrons, and light fragments are found to be emitted preferentially perpendicular to the reaction plane [10–12]. Such an effect was predicted as a hydrodynamical "squeeze out" of nuclear matter from the dense reaction zone [13]. However, in contrast to the in-plane flow, only a minor fraction of the participating nucleons—mainly those with large transverse momenta—take part in this off-plane collective motion [12]. The azimuthal emission pattern of pions was also found to be strongly anisotropic at midrapidity. Similar to the nucleons, the pions are emitted preferentially perpendicular to the reaction plane [14–16]. This effect is independent of the pion charge and—as for protons—most pronounced for large transverse momenta and semicentral collisions. The pion nonisotropic emission pattern was attributed to shadowing effects caused by rescattering off (or absorption by) the spectator fragments [17]. The K^+ mean free path for rescattering in nuclear matter is substantially longer than the one of pions. Therefore, much smaller anisotropies of the K^+ azimuthal emission pattern were expected.

In this Letter we present evidence for azimuthal anisotropic emission of K^+ mesons measured in Au + Au collisions at a beam kinetic energy of 1A GeV. In-medium effects will be most pronounced in this very heavy collision system. The bombarding energy is well below the K^+ production threshold ($E_{\mathrm{thres}}^{NN} = 1.58$ GeV for free NN collisions). Therefore, the kaons can hardly be produced in first chance NN collisions but are created inside the dense reaction zone by multistep processes involving more than two nucleons.

The experiment was performed with the kaon spectrometer at the heavy ion synchrotron at GSI [18]. This magnetic spectrometer has a large acceptance in a solid angle and momentum ($\Omega \approx 30$ msr, $p_{\max}/p_{\min} \approx 2$). The short distance of 5–6.5 m from target to focal plane minimizes kaon decays in flight. Particle identification and trigger are based on a measurement of momentum and time of flight. Background suppression is performed by track reconstruction based on three large-area multiwire chambers. Two scintillator hodoscopes are used for event characterization. The centrality of the reaction is determined by the multiplicity of charged particles measured with the large-angle hodoscope. This detector consists of 84 modules and covers polar emission angles between 12° and 48°. The orientation of the event plane is reconstructed from the azimuthal emission angles of the charged projectile spectators. These particles are identified (up to $Z = 8$) by their energy loss and time of flight measured with the small-angle hodoscope. This detector array, which consists of 380 modules, is positioned 7 m downstream from the target and covers polar angles from 0.5° to 11°.

The measurement was performed with a ^{197}Au beam accelerated to an energy of 1A GeV with an intensity of about 5×10^7 ions per spill. Because of the energy loss in the ^{197}Au target of 1.93 g/cm^2 thickness the beam energy was reduced on the average by 4%. The K^+ mesons are measured at polar angles of $\Theta_{\rm lab} =$ 34°, 44°, and 54° over a momentum range of $260 < p_{\rm lab} < 1950$ MeV/c. About 25 000 K^+ mesons have been registered.

In order to determine the particle azimuthal emission angle, the reaction plane has to be reconstructed. This is done by the transverse momentum method [19]. The orientation of the reaction plane is determined for each event by the azimuthal direction of the total transverse momentum of all spectator particles detected in the small-angle hodoscope. The orientation of the event plane can be determined with an accuracy of 36° (standard deviation) for semicentral collisions and 55° for peripheral and central collisions [12].

Figure 1 shows the azimuthal distribution of kaons detected with the spectrometer in peripheral ($b \leq 5$ fm), semicentral ($b = 5-10$ fm) and central collisions ($b \geq 10$ fm). The angle ϕ is relative to the event plane. The kaons are measured at normalized rapidities of $0.2 \leq y/y_{\rm proj} < 0.8$ and within a transverse momentum range of $0.2 \leq p_t < 0.8$ GeV/c. For peripheral and semicentral events the K^+ azimuthal distribution exhibits clear maxima at $\phi = 90°$ and $\phi = -90°$ corresponding to an enhanced emission perpendicular to the reaction plane. For near central collisions the event plane is less well defined and therefore the effect becomes less pronounced.

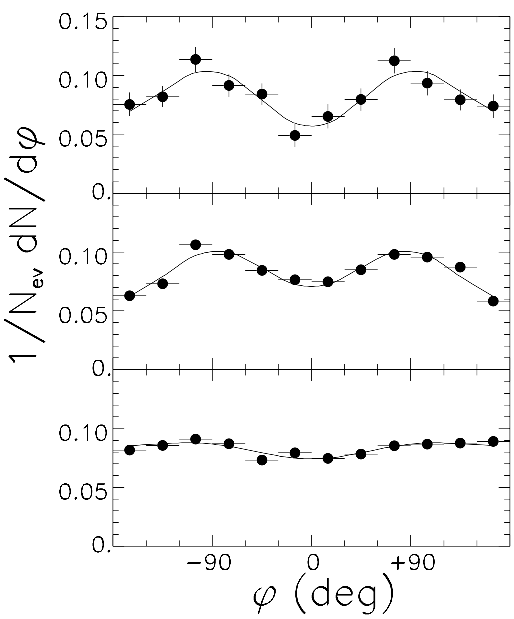

FIG. 1. K^+ azimuthal angular distribution for peripheral ($b \geq 10$ fm), semicentral ($b = 5-10$ fm), and central ($b \leq 5$ fm) Au + Au collisions at 1A GeV (from top to bottom). The data cover normalized rapidities in the interval $0.2 \leq y/y_{\rm proj} < 0.8$ and transverse momenta in the interval $0.2 \leq p_t < 0.8$ GeV/c. The lines represent fits to the data (see text).

The azimuthal emission pattern can be parametrized by $N(\phi) \propto 1 + a_1 \cos\phi + a_2 \cos 2\phi$. The parameter a_1 quantifies the in-plane emission of the particles parallel ($a_1 > 1$) or antiparallel ($a_1 < 1$) to the impact parameter vector, whereas a_2 stands for an elliptic emission pattern which may be aligned with the event plane ($a_2 > 0$) or oriented perpendicular to the event plane ($a_2 < 0$). The parameters were determined by a fit to the data and corrected for the uncertainty in the reaction plane reconstruction by $a'_{1,2} = a_{1,2}/\langle\cos 2\Delta\phi\rangle$. The values of $\langle\cos 2\Delta\phi\rangle$ have been determined by a Monte Carlo simulation and vary between 0.3 for peripheral and central collisions and 0.5 for semicentral collisions (for details see [12]). The results of the fits including the correction are shown in Fig. 1 (solid lines) and the parameters are listed in Table I. The strength of the azimuthal anisotropy is given by the ratio R which is the number of K^+ mesons emitted perpendicular to the event plane divided by the number of K^+ mesons emitted parallel to the event plane (for $a_2 < 0$):

$$R = \frac{N(90°) + N(-90°)}{N(0°) + N(180°)} = \frac{1 - a'_2}{1 + a'_2}.$$

The values of R for K^+ mesons emitted around midrapidity in peripheral, semicentral, and central collisions are given in Table I. Note that these values are corrected for the resolution of the reaction-plane determination.

Similar values for the azimuthal asymmetry parameter R have been found for pion emission in the same reaction [14,16]. Figure 2 shows the ratio R as a function of the transverse momentum p_t both for π^+ and K^+ mesons emitted in semicentral Au + Au collisions at 1A GeV around midrapidity. The kaon data are grouped into three points because of limited statistics. Within the error bars, the kaon azimuthal asymmetry parameter R does not increase with increasing transverse momentum in contrast to the one for pions. This implies that the K^+ transverse momentum distributions will not vary as a function of the azimuthal angle. The centrality dependence of R is different for K^+ mesons (see Fig. 1) and pions [16]: the pion azimuthal asymmetry has a maximum around semicentral collisions whereas for K^+ mesons no reduction of R in peripheral collisions is observed. The K^+ azimuthal asymmetry rather increases weakly with

TABLE I. Results of the fit $N(\phi) \propto 1 + a_1' \cos\phi + a_2' \cos 2\phi$ to the K^+ azimuthal distributions for normalized rapidities of $0.2 \le y/y_{\mathrm{proj}} < 0.8$. The coefficients a_1' and a_2' are corrected for the experimental resolution of the event plane determination. The values of a_1' are subject to an additional systematical error of 0.06.

Centrality	a_1'	a_2'	R	χ^2
Peripheral ($b \ge 10$ fm)	-0.063 ± 0.048	-0.256 ± 0.051	1.68 ± 0.18	0.79
Semicentral ($5 < b < 10$ fm)	0.064 ± 0.018	-0.219 ± 0.021	1.56 ± 0.06	2.13
Central ($b \le 5$ fm)	-0.066 ± 0.014	-0.044 ± 0.014	1.09 ± 0.03	1.5

increasing impact parameter, i.e., with the increasing size of the spectator remnants.

It is unlikely that the pion and the kaon azimuthal asymmetries are both caused by pure rescattering on the spectator fragments because of the very different mean free paths of K^+ mesons and pions in nuclear matter. The total cross section for $\pi^+ p$ scattering with pion momenta of 0.4–0.5 GeV/c is 80–40 mb [20] corresponding to a mean free path of $\lambda_\pi = 0.8$–1.6 fm in normal nuclear matter. In contrast the $K^+ p$ total cross section is about 12 mb for kaon momenta below 1 GeV/c [20] resulting in a mean free path of $\lambda_{K^+} \approx 5$ fm. Indeed, transport models predict a very small azimuthal anisotropy for semicentral ($b = 7$ fm) Au + Au collisions at 1A GeV when considering only K^+ rescattering [21]. The result of this relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) calculation is shown in Fig. 3 (dashed line) together with the data taken around midrapidity ($0.4 \le y/y_{\mathrm{proj}} < 0.6$). On the other hand, the pronounced K^+ out-of-plane emission of the experimental data is reproduced by the calculations if an additional repulsive in-medium K^+N potential is taken into account (solid line in Fig. 3). Similar conclusions are obtained from a quantum molecular dynamics calculation [22].

Another experimental evidence for an in-medium change in the kaon-nucleon potential was predicted to be the disappearance of K^+ directed flow into the reaction plane [9]. Related information on the in-plane emission of K^+ mesons is obtained by dividing our K^+ sample into intervals of rapidity. The K^+ azimuthal distributions for semicentral collisions near target rapidity ($0.2 \le y/y_{\mathrm{proj}} < 0.4$), midrapidity ($0.4 \le y/y_{\mathrm{proj}} < 0.6$), and projectile rapidity ($0.6 \le y/y_{\mathrm{proj}} < 0.8$) are parametrized with the function $N(\phi) \propto 1 + a_1 \cos\phi + a_2 \cos 2\phi$. The resulting parameters (corrected for the uncertainty in the reaction plane reconstruction) are given in Table II. The coefficient a_1' which measures the strength of the in-plane emission is subject to a systematical error of 0.06 which is due to the uncertainty of the beam position at the small-angle hodoscope. Within the statistical and systematical errors, the a_1' values in Table II are compatible with zero for all

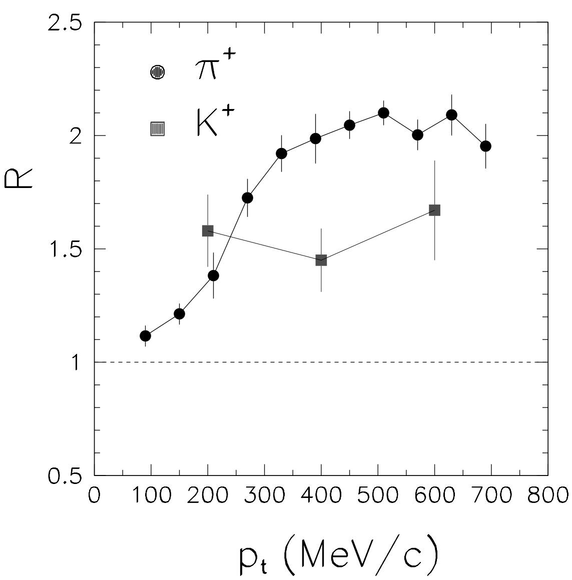

FIG. 2. Azimuthal anisotropy parameter R as a function of transverse momenta for pions and K^+ mesons measured in semicentral Au + Au collisions at 1A GeV. The data cover normalized rapidities in the interval $0.2 \le y/y_{\mathrm{proj}} < 0.8$ and transverse momenta in the interval $0.2 \le p_t < 0.8$ GeV/c.

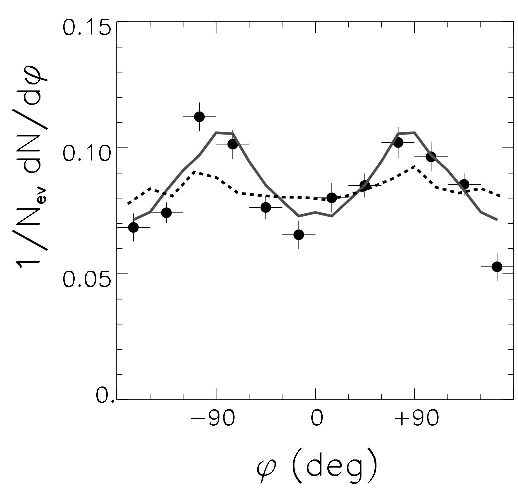

FIG. 3. K^+ azimuthal angular distribution measured in semicentral ($b = 5$–10 fm) Au + Au collisions at 1A GeV around midrapidity ($0.4 \le y/y_{\mathrm{proj}} < 0.6$) for K^+ transverse momenta of $0.2 \le p_t < 0.8$ GeV/c. The lines represent results of RBUU calculations for an impact parameter of $b = 7$ fm [21] without (dashed line) and with an in-medium K^+N potential (solid line). Both calculations take into account kaon-nucleon rescattering.

TABLE II. Results of the fit $N(\phi) \propto 1 + a_1' \cos\phi + a_2' \cos 2\phi$ to the K^+ azimuthal distributions for semicentral collisions and for three ranges of rapidity. The coefficients a_1' and a_2' are corrected for the experimental resolution of the event plane determination. The values of a_1' are subject to an additional systematical error of 0.06.

y/y_{proj}	a_1'	a_2'	R	χ^2
0.2–0.4	0.084 ± 0.027	−0.20 ± 0.028	1.48 ± 0.08	2.06
0.4–0.6	0.043 ± 0.025	−0.257 ± 0.029	1.68 ± 0.1	2.35
0.6–0.8	0.038 ± 0.029	−0.174 ± 0.030	1.42 ± 0.08	0.95

rapidity bins. We find no signature for the existence of enhanced in-plane emission of K^+ mesons near target or projectile rapidity. This result is in agreement with the absence of K^+ flow as measured in a lighter system at higher bombarding energies [8]. In the case of pions, a small antiflow has been found in Au + Au collisions [23]. This effect was explained by pion rescattering on the spectators in the late stage of the collision [24].

In summary, we have measured K^+ triple differential cross sections in Au + Au collisions at 1*A* GeV. The K^+ azimuthal angular distribution is found to be anisotropic in peripheral and semicentral collisions. The kaons are emitted preferentially perpendicular to the reaction plane. The K^+ azimuthal anisotropy increases weakly with an increasing impact parameter. In contrast to pions, no variation of the azimuthal asymmetry with transverse momentum of the K^+ mesons was found within the large experimental errors. No in-plane flow of K^+ mesons was observed close to target and projectile rapidity.

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