Enhanced Out-of-plane Emission of $K^+$ Mesons
observed in Au+Au Collisions at 1 AGeV

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Abstract

The azimuthal angular distribution of $K^+$ mesons has been measured in Au + Au collisions at 1 AGeV. In peripheral and semi-central collisions, $K^+$ mesons preferentially are emitted 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.
Relativistic nucleus-nucleus collisions provide the unique possibility to study both the
behaviour 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 an 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 behaviour comes from a measurement of the average $K^+$ momentum in the event
plane in Ni+Ni collisions at 1.93 AGeV: the directed in-plane flow found for protons and
lambda 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 semi-central 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 1 AGeV. In-medium effects will be most pronounced in this very heavy collision system. The chosen bombarding energy is well below the $K^+$ production threshold ($E_{NN}^{thres} = 1.58$ 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 (KaoS) at the heavy ion synchrotron at GSI [18]. This magnetic spectrometer has a large acceptance in 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 multi-wire 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 1 AGeV with an intensity of about $5 \times 10^7$ ions per spill. Due to the energy loss in the $^{197}$Au target of 1.93 g/cm² thickness the beam energy was reduced on the average by 4%. The $K^+$ mesons are measured at polar angles of $\Theta_{lab}=34^0$, 44° and 54° over a momentum range of $260 < p_{lab} < 1950$ MeV/c. About 25000 $K^+$ 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.
orientation of the event plane can be determined with an accuracy of 36 degrees (standard deviation) for semi-central collisions and 55 degrees for peripheral and central collisions [12].

Figure 1 shows the azimuthal distribution of kaons detected with the spectrometer in peripheral (b≤5 fm), semi-central (b=5-10 fm) and central collisions (b≥10 fm). The angle φ is relative to the event plane. The kaons are measured at normalized rapidities of 0.2≤ y/y_{proj} <0.8 and within a transverse momentum range of 0.2 GeV/c≤ p_t <0.8 GeV/c. For peripheral and semi-central events the K^+ azimuthal distribution exhibits clear maxima at φ = 90° and φ = −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.

The azimuthal emission pattern can be parameterized by N(φ)∝ 1+ a_1 cos φ + a_2 cos 2φ. 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}/< cos 2Δφ >. The values of < cos 2Δφ > have been determined by a Monte Carlo simulation and vary between 0.3 for peripheral and central collisions and 0.5 for semi-central collisions (for details see [16]). The results of the fits including the correction are shown in Fig. 1 (solid lines) and the parameters are listed in Table 1. 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):

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

The values of R for K^+ mesons emitted around midrapidity in peripheral, semi-central and central collisions are given in Table 1. 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 emis-
sion in the same reaction \[14,16\]. Figure 2 shows the ratio $R$ as a function of the transverse momentum $p_t$ both for $\pi^+$ and $K^+$ mesons emitted in semi-central $Au + Au$ collisions at 1 AGeV around midrapidity. The kaon data are grouped into 3 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 semi-central collisions whereas for $K^+$ mesons no reduction of $R$ in peripheral collisions is observed. The $K^+$ azimuthal asymmetry rather increases weakly with increasing impact parameter i.e. with 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 $K^+$ very small azimuthal anisotropy for semi-central ($b = 7$ fm) $Au+Au$ collisions at 1 AGeV when considering only $K^+$ rescattering \[21\]. The result of this RBUU calculation is shown in Fig.3 (dashed line) together with the data taken around midrapidity ($0.4 \leq y/y_{proj} < 0.6$). 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 QMD 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 \[3\]. 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 semi-central collisions near
target rapidity ($0.2 \leq y/y_{proj} < 0.4$), midrapidity ($0.4 \leq y/y_{proj} < 0.6$) and projectile rapidity ($0.6 \leq y/y_{proj} < 0.8$) are parameterized 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 2. 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 2 are compatible with zero for all rapidity bins. We find no signature for the existence of an 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 AGeV for different polar angles. The $K^+$ azimuthal angular distribution is found to be anisotropic in peripheral and semi-central collisions. The kaons are emitted preferentially perpendicular to the reaction plane. The $K^+$ azimuthal anisotropy increases weakly with 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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Table 1: 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 $0.2 \leq y/y_{proj} < 0.8$. 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       | $\chi^2$ |
|-----------------------------|------------|------------|---------|----------|
| peripheral (b$\geq$10 fm)  | -0.063$\pm$0.048 | -0.256$\pm$0.051 | 1.68$\pm$0.18 | 0.79     |
| semi-central (5 fm $<$b$<$10 fm) | 0.064$\pm$0.018 | -0.219$\pm$0.021 | 1.56$\pm$0.06 | 2.13     |
| central (b$\leq$5 fm)      | -0.066$\pm$0.014 | -0.044$\pm$0.014 | 1.09$\pm$0.03 | 1.5      |

Table 2: Results of the fit $N(\phi) \propto 1 + a'_1 \cos \phi + a'_2 \cos 2\phi$ to the $K^+$ azimuthal distributions for semi-central 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       | $\chi^2$ |
|--------------|------------|------------|---------|----------|
| 0.2-0.4      | 0.084$\pm$0.027 | -0.20$\pm$0.028 | 1.48$\pm$0.08 | 2.06     |
| 0.4-0.6      | 0.043$\pm$0.025 | -0.257$\pm$0.029 | 1.68$\pm$0.1  | 2.35     |
| 0.6-0.8      | 0.038$\pm$0.029 | -0.174$\pm$0.030 | 1.42$\pm$0.08 | 0.95     |
Fig. 1: K\(^+\) azimuthal angular distribution for peripheral (b ≥ 10 fm), semi-central (b = 5 - 10 fm) and central (b ≤ 5 fm) Au+Au collisions at 1 AGeV (from top to bottom). The data cover normalized rapidities in the interval 0.2 ≤ y/y_{proj} < 0.8 and transverse momenta in the interval 0.2 GeV/c ≤ p_t < 0.8 GeV/c. The lines represent fits to the data (see text).

Fig. 2: Azimuthal anisotropy parameter R as a function of transverse momenta for pions and K\(^+\) mesons measured in semi-central Au+Au collisions at 1 AGeV. The data cover normalized rapidities in the interval 0.2 ≤ y/y_{proj} < 0.8 and transverse momenta in the interval 0.2 GeV/c ≤ p_t < 0.8 GeV/c.

Fig. 3:

K\(^+\) azimuthal angular distribution measured in semi-central (b = 5 - 10 fm) Au+Au collisions at 1 AGeV around midrapidity (0.4 ≤ y/y_{proj} < 0.6) for K\(^+\) transverse momenta of 0.2 GeV/c ≤ p_t < 0.8 GeV/c. The lines represent results of RBUU calculations for an impact parameter of b = 7 fm \cite{21} without (dashed line) and with an in-medium KN potential (solid line). Both calculations take into account kaon-nucleon rescattering.
FIGURES

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FIG. 2.
FIG. 3.