Observation of different azimuthal emission patterns for $K^+$ and of $K^-$ mesons in Heavy Ion Collisions at 1-2 $A\cdot$GeV

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Azimuthal distributions of $\pi^+, K^+$ and $K^-$ mesons have been measured in Au+Au reactions at 1.5 $A\cdot$GeV and Ni+Ni reactions at 1.93 $A\cdot$GeV. In semi-central collisions at midrapidity, $\pi^+$ and $K^+$ mesons are emitted preferentially perpendicular to the reaction plane in both collision systems. In contrast for $K^-$ mesons in Ni+Ni reactions an in-plane elliptic flow was observed for the first time at these incident energies.

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Relativistic heavy ion collisions provide a unique opportunity to study both the behavior of nuclear matter at high densities as well as the properties of hadrons in dense nuclear matter. In particular, strange mesons are considered to be sensitive to in-medium modifications. Theory predicts a repulsive $K^+N$ potential and an attractive $K^-N$ potential in dense matter. It is suggested that the latter effect leads to a condensate of $K^-$ mesons in the interior of the neutron stars, causing dramatic consequences for the neutron star stability.

Microscopic transport calculations simulating heavy-ion collisions predict measurable consequences of the in-medium modifications of strange mesons. The $KN$ potentials reduce the $K^+$ yield and enhance the $K^-$ yield, resulting in an increase of the $K^-/K^+$ ratio.

First experimental evidence for in-medium modifications of $K^-$ mesons in dense nuclear matter was the observation that the $K^-/K^+$ ratio was enhanced in Ni+Ni collisions as compared to nucleon-nucleon collisions. A large $K^-/K^+$ ratio was also found in C+C collisions and in Au+Au collisions. In heavy-ion collisions, however, strangeness-exchange reactions like $\pi\Lambda \rightarrow K^-N$ contribute significantly to the production of $K^-$ mesons. This process, although taken into account by transport calculations, reduces the sensitivity of the $K^-$ meson yield to the in-medium $KN$ potential.

Another observable affected by in-medium effects is the azimuthal emission pattern of $K^+$ and $K^-$ mesons in heavy-ion collisions. $K^+$ and $K^-$ mesons experience different potentials in nuclear matter: While the scalar potential acts attractively on both kaon species, the vector potential repels $K^+$ mesons and attracts $K^-$ mesons. For the $K^+$ mesons these two contributions almost cancel each other leading to a small repulsive $K^+N$ interaction. The superposition of the two attractive interactions results in a strongly attractive potential for $K^-$ mesons.

A repulsive $K^+N$ potential would repel the $K^+$ mesons from the bulk of the nucleons and therefore cause an preferred out-of-plane emission of the $K^+$ mesons at midrapidity and a directed flow opposite to the nucleons at target and projectile rapidity. These effects were found in experiments and interpreted as evidence for a repulsive $K^+N$ potential.

The propagation of $K^-$ mesons in nuclear matter is governed by a large $K^-p$ cross section of up to 100 mb which is dominated by inelastic scattering via the strangeness-exchange reaction $\pi Y \leftrightarrow K^-N$ with $Y = \Lambda, \Sigma$. Therefore, one would expect a pronounced azimuthal anisotropy of the $K^-$ meson emission in heavy-ion collisions due to the interaction of $K^-$ mesons with spectator matter. However, when taking into account the strongly attractive in-medium $K^-N$ potential, transport calculations predict an almost isotropic azimuthal emission pattern at midrapidity.

In this Letter we present experimental data on the azimuthal distributions of both $K^+$ and $K^-$ mesons in nucleus-nucleus collisions. We have measured two systems: Ni+Ni at 1.93 $A\cdot$GeV (both for $K^+$ and $K^-$ mesons) and Au+Au at 1.5 $A\cdot$GeV (only $K^+$ mesons). For comparison also results from an analysis of $\pi^+$ mesons are given. An azimuthal distribution of $K^-$ mesons emitted in heavy-ion collisions at subthreshold
beam energies is shown for the first time.

The experiments were performed with the Kaon Spectrometer (KaoS) at the heavy-ion synchrotron (SIS) at GSI in Darmstadt [14], using an Au beam of 1.5 AGeV impinging on an Au target (0.96 g/cm²) and a Ni beam of 1.93 AGeV on a Ni target (0.68 g/cm²). The particles were identified using the momentum and time-of-flight information of the magnetic spectrometer, and two hodoscopes were used for event characterization [14]. The Large Angle Hodoscope is used to derive the centrality of the collision from the multiplicity of charged particles measured in the polar angle range 12° < θlab < 48°. The orientation of the event plane was reconstructed from the azimuthal emission angle of the charged projectile spectators using the transverse momentum method [16]. These particles were identified (up to Z = 8) by their energy loss and their time of flight as measured with the Small Angle Hodoscope located about 7 m downstream from the target covering polar angles between 0.5° and 11°. The resolution in the determination of reaction plane is (ΔΦ)1/2 = 37° for the Au-system and (ΔΦ)1/2 = 61° for the Ni-system.

Figure 1 shows the azimuthal distributions of K+ and π+ mesons for semi-central Au+Au collisions at 1.5 AGeV. The distributions are corrected for the angular resolution of the reaction plane determination [14]. The data are fitted using the first two components of a Fourier series

\[ \frac{dN}{d\phi} \sim 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) \] (1)

resulting in values for v1 and v2, as given in the figures together with the statistical errors. The determination of the coefficient v1 is subject to an additional systematic error of 0.04.

Both π+ and K+ mesons exhibit a pronounced enhancement at φ = ±90°, i.e. perpendicular to the reaction plane. For π+ mesons this effect can be interpreted as rescattering and absorption at the spectator fragments. The data are in agreement with previous observations [11, 13].

The study of Ni+Ni collisions was performed at a higher incident energy of 1.93 AGeV. The resulting higher production cross section for K− mesons provides an opportunity to study both charged kaon species. The data are shown in Fig. 4 along with π+ mesons for semi-central Ni+Ni collisions. Both π+ and K+ mesons follow the same trend already observed in Au+Au collisions. The values for v2 are smaller than in Au+Au as one might expect for the smaller system. In contrast to the π+ and K+ mesons, the K− mesons show an in-plane enhancement.

This “positive” (in-plane) elliptic flow of particles is observed for the first time in heavy-ion collisions at SIS energies. In contrast to this observation one would expect a preferential out-of-plane emission (negative elliptic flow) of K− mesons due to their large absorption cross section in spectator matter.

Figure 1: Azimuthal distribution of π+ and K+ mesons for semi-central Au+Au collisions at 1.5 AGeV. The data are corrected for the resolution of the reaction plane and refer to impact parameters of 5.9 fm < b < 10.2 fm, rapidities of 0.3 < y/ybeam < 0.7 and momenta of 0.2 GeV/c < p_t < 0.8 GeV/c. The lines are fits with function 1 resulting in the values for v1 and v2 as given in the figure.

A depletion of the expected out-of-plane emission pattern of K− mesons might be due to the fact that they are produced via strangeness-exchange reactions. This causes a delay in the freeze-out of the K− mesons [12, 13, 18], and, hence, a reduced shadowing effect by the spectator fragments which have moved further away. The observed in-plane emission of K− mesons, however, cannot be easily explained with this scenario.

In order to quantitatively explain the K+ and K− meson azimuthal distributions we compare in Fig. 9 our data to recent results of the Iospin Quantum Molecular Dynamics (IQMD) model [17]. This transport calculation takes into account both the space-time evolution of the reaction system and the in-medium properties of the strange mesons. The dashed and solid lines represent results of calculations without and with in-medium potentials, respectively. In the case of the K+ mesons (upper panel of Fig. 9) the effect of the repulsive K+N potential is small in this model. A large fraction of the observed out-of-plane enhancement, in contrast to other models [12, 13, 15], is caused by the scattering of K+ mesons. Another transport code (HSD) [13] predicts a dominant influence of the potential on the emission pattern of the K+ mesons. In the system Au+Au at 1 AGeV where both size and life time of the fireball are larger than in...
the Ni+Ni case, the effect of the repulsive $K^+N$ potential was studied using the RBUU code and was found to be very important.

In the lower part of Fig. 3 we compare a calculation without (dashed) and with (solid) $K^-N$ potential. When neglecting the $K^-N$ potential, the calculation predicts a weak in-plane elliptic flow caused by shadowing. This effect is rather small because of the late emission of $K^-$ mesons. When taking into account the attractive in-medium $K^-N$ potential the model is able to describe the experimental in-plane elliptic flow pattern much better. Model calculations with the HSD code predict a flat azimuthal distribution both with and without a $K^-N$ potential and, hence cannot explain the observed in-plane flow of $K^-$ mesons.

In summary, we have measured the azimuthal emission patterns of $\pi$ and $K$ mesons in heavy-ion collisions at threshold beam energies. We found a pronounced out-of-plane emission (negative elliptic flow) for the $K^+$ mesons confirming previous results. We presented new data on the azimuthal angle distribution of $K^-$ mesons which exhibit a positive (in-plane) elliptic flow pattern, which is in contrast to all other measured particles exhibiting a preferred out-of-plane emission.

This observation can be explained by a transport model (IQMD) by a late emission of $K^-$ mesons and assuming an attractive in-medium $K^-N$ potential. Hence, the distribution of strange mesons in space and their multiplicity which has been used so far, are independent probes to extract information on in-medium properties at high densities.

FIG. 2: Azimuthal distribution of $\pi^+$, $K^+$ and $K^-$ mesons for semi-central Ni+Ni collisions at 1.93 A·GeV. The data are corrected for the resolution of the reaction plane and refer to impact parameters of $3.8 \text{ fm} < b < 6.5 \text{ fm}$, rapidities of $0.3 < y/y_{beam} < 0.7$ and momenta of $0.2 \text{ GeV/c} < p_t < 0.8 \text{ GeV/c}$. The lines are fits with function $f$ resulting in the values for $v_1$ and $v_2$ as given in the figure.

FIG. 3: Comparison of the data from Ni+Ni reactions at 1.93 A·GeV with IQMD model calculations. The data are corrected for the resolution of the reaction plane and refer to impact parameters of $3.8 \text{ fm} < b < 6.5 \text{ fm}$, rapidities of $0.3 < y/y_{beam} < 0.7$ and momenta of $0.2 \text{ GeV/c} < p_t < 0.8 \text{ GeV/c}$.
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