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Azimuthal emission patterns of $K^+$ mesons have been measured in Ni + Ni collisions with the FOPI spectrometer at a beam kinetic energy of 1.91 A GeV. The transverse momentum $p_T$ integrated directed and elliptic flow of $K^+$ and $K^-$ mesons as well as the centrality dependence of $p_T$- differential directed flow of $K^+$ mesons are compared to the predictions of HSD and IQMD transport models. The data exhibits different propagation patterns of $K^+$ and $K^-$ mesons in the compressed and heated nuclear medium and favors the existence of a kaon-nucleon in-medium potential, repulsive for $K^+$ mesons and attractive for $K^-$ mesons.

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I. INTRODUCTION

Relativistic heavy-ion collisions at bombarding energies of 1 - 2 A GeV provide the unique possibility to study nuclear matter at high temperatures, around 100 MeV, and baryon densities about 2 - 3 times the normal nuclear matter density ($\rho_0$) [1, 2]. Under these conditions, the properties of hadrons may be altered as a result of various non-trivial in-medium effects like the partial restoration of the spontaneously broken chiral symmetry, the modified baryon-meson couplings, and the nuclear potential. Whether and how hadronic properties, such as masses, widths and dispersion relations are mod-
ified in the hot and dense nuclear medium is a topic of great current interest. In particular, strange mesons produced around the production threshold energies in nucleon-nucleon collisions are considered to be sensitive to in-medium modifications. Various theoretical approaches agree qualitatively predicting slightly repulsive $K N$- and strongly attractive $\bar{K} N$ potentials \cite{3}. The depth of the $\bar{K} N$ potential at finite densities is, however, not well constrained by currently available data and is a matter of an active theoretical dispute \cite{4}. If the $K^- N$ potential is sufficiently deep, this might have exciting consequences for the stability of neutron stars \cite{5} or for the existence of deeply bound $K^-$ states \cite{6}.

Heavy-ion experiments, with the capability to identify kaons and antikaons, have been performed with the KaoS, FOPI and HADES detector systems at the heavy-ion synchrotron (SIS) of GSI, aiming at measuring the in-medium properties. A significantly enhanced yield of $K^-$ mesons relative to that of $K^+$ \cite{7} \cite{8}, an increase of the $K^-/K^+$ ratio at low kinetic energy of kaons \cite{8} \cite{9}, and different freeze-out conditions of $K^+$ and $K^-$ mesons were observed \cite{10}, the latter at least partially explained by the production of $\phi$ mesons \cite{11}. After the suggestion that the $KN$ potential should manifest itself in the collective motion of kaons, referred to as ‘flow’ \cite{12}, a lot of effort was invested to deduce the strength of the kaon potential by measuring the kaon flow in heavy-ion collisions \cite{13} \cite{14} \cite{15}. Experimental difficulties due to the small production rate of $K^-$ mesons in comparison to $K^+$ in the SIS energy regime restrict the measurements. Currently available flow results for $K^-$ mesons are not sufficient to draw conclusions on the existence and strength of the $\bar{K} N$ in-medium potential.

In this article, we report for the first time on the simultaneous measurements of $K^+$ and $K^-$ mesons with a large acceptance spectrometer at an incident beam energy of 1.91 AGeV that is close to the various strangeness production threshold energies. The data are compared to state-of-the-art transport calculations with and without the assumption of an in-medium potential. In particular, we show the azimuthal anisotropy of $K^-$ mesons in a wide range of rapidity and the centrality dependence of $p_T$ differential flow of $K^+$ mesons.

II. DATA ACCUMULATION AND ANALYSIS

The experiment was performed with the FOPI spectrometer, an azimuthally symmetric apparatus comprising several sub detectors \cite{17}. Recently a high resolution highly granular time-of-flight (ToF) Barrel based on Multi-strip Multi-gap Resistive Plate Counters (MMRPC) \cite{18} was added to the FOPI apparatus improving significantly the kaon identification capability. Charged kaons are identified based on the ToF-information from MMRPC and Plastic Scintillator Barrel (PSB), combined with the momentum information from the Central Drift Chamber (CDC, $27^\circ < \theta_{lab} < 113^\circ$ ), see Table I.

The acceptance range of the detector for $K^\pm$ is shown in the upper panel of Fig. I in terms of normalized transverse momentum, $p_T/m_K$, and normalized rapidity, $y_{(0)} = y_{lab}/y_{cm} - 1$, defined to be $+1$ ($-1$) at projectile (target) rapidity. About $69 \times 10^6$ events were recorded, triggering on the most central 60\% of the total geometrical cross section ($\sigma_{trig} = 1.6 \text{ b}$). In total, 233,300 $K^+$ and 5,200 $K^-$ mesons were identified within $2\sigma$ around the fitted signal peaks from ToF mass spectra (as visualized for the MMRPC in Fig. I lower panel). In order to account for the contamination from pions and protons as well as misidentified tracks the background distribution was estimated in a worst-case scenario, i.e. as linear background connecting the minima around the fitted signal peaks in the mass spectra. Following these definitions for

| ToF    | $\theta_{lab}$ (deg) | $K^+$ $p_{lab}$ (GeV/c) | $S/B$ | $K^-$ $p_{lab}$ (GeV/c) | $S/B$ |
|--------|-----------------------|-------------------------|-------|-------------------------|-------|
| MMRPC  | [30, 55]              | [0.13, 0.9]             | > 22  | [0.13, 0.7]             | > 8   |
| PSB    | [55, 110]             | [0.13, 0.55]            | > 10  | [0.13, 0.45]            | > 4   |

FIG. 1: (color online) Upper panel: Measured yield of $K^+$ and $K^-$ mesons: $p_T/m_K$ as a function of $y_{(0)}$. The contour levels correspond to logarithmically increasing intensity. The solid curves denote the geometrical limits of the detector acceptance ($\theta_{lab} = 30^\circ, 55^\circ$ and $110^\circ$). The dashed curves corresponds to $p_{lab} = 0.55$ and $0.9 \text{ GeV/c}$ for $K^+$ (left) and $p_{lab} = 0.45$ and $0.7 \text{ GeV/c}$ for $K^-$ (right). Lower panel: The mass spectra from MMRPC for $Z = 1$ and $-1$. The solid lines represent Gaussian fit functions for the signal and exponential functions for the background (see text for details).
function of $y$ total event sample (a) (see Table II) are presented as
duced the statistical error, Fig. 2 also contains a
by a systematic uncertainty (boxes in Fig. 2 and Fig. 4).
[24], a systematic deviation, which is taken into account
with conditions on the baryon multiplicity (Mul), shown
in Table II. The baryon multiplicity contains all charged
particles from the Plastic Wall (6.5° < $\theta_{lab}$ < 23°) and
p, d, t, $^3$He and $^4$He from the CDC. The reaction plane
was reconstructed event-wise by the transverse momen-
tum method [19].
The phenomenon of collective flow [20] can be quan-
titatively described in terms of anisotropies of the azi-
muthal emission pattern, expressed by a Fourier series:
\[
dN\over d\phi \propto (1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + ...),
\]
where $\phi$ is the azimuthal angle of the outgoing particle
with respect to the reaction plane [21]. The first order
Fourier coefficient, $v_1$, describes the collective sideward
deflection of particles in the reaction plane, called ‘di-
rected flow’. The second order Fourier coefficient, $v_2$,
describes the emission pattern in- versus out- of the re-
action plane, referred to as ‘elliptic flow’ [15, 22]. The
Fourier coefficients are corrected event-wise for the ac-
curacy of the reaction plane determination according to
the Ollitrault method [23]. The mean correction values
are given in Table II. Note that the most peripheral events
(Mul < 20) were rejected to assure a minimal accuracy of
the reaction plane determination.

TABLE II: Definition of event classes: (a) total, (p) periph-
eral and (c) central events. The corresponding cross section
$\sigma$, mean impact parameter $\langle b \rangle$, the r.m.s. of $b$ distribution: $\Delta b$ and the reaction plane correction factors $f_1$ for $v_1$ and $f_2$ for $v_2$ are listed.

| Mul  | $\sigma$ (b) | $\langle b \rangle \pm \Delta b$ (fm) | $f_1$ | $f_2$ |
|------|-------------|---------------------------------|------|------|
| (a)  | 20, 90      | 1.09 ± 0.10                     | 3.90 ± 1.41 | 1.5 ± 0.1 | 3.0 ± 0.1 |
| (p)  | 20, 48      | 0.79 ± 0.05                     | 4.54 ± 0.95 | 1.5 ± 0.1 | 3.0 ± 0.1 |
| (c)  | 49, 90      | 0.30 ± 0.05                     | 2.11 ± 0.80 | 1.6 ± 0.1 | 3.1 ± 0.2 |

III. RESULTS

The experimental data on $v_1$ and $v_2$ of $K^\pm$ for the
total event sample (a) (see Table II) are presented as
function of $y_{(0)}$ in Fig. 2 and Fig. 3. $v_1$ is by definition
antisymmetric with respect to mid-rapidity, therefore it
should vanish at mid-rapidity for a symmetric colliding
system. However, we observe, like in other FOPI data
24, a systematic deviation, which is taken into account
by a systematic uncertainty (boxes in Fig. 2 and Fig. 3).
The $v_1$ values of $K^-$ are compatible with zero within the
statistical sensitivity of the data (Fig. 2). In order to re-
duce the statistical error, Fig. 2 also contains a $K^-$ data
point with an upper momentum limit of 1.0 GeV/c (star
symbol) from subset of runs with improved resolution.

Near target rapidity $K^+$ mesons show a collective in-
plane deflection in the direction opposed to that of pro-
tons (Fig. 2). This pattern is called ‘anti-flow’ and is in
agreement with previous FOPI measurement [15]. Addi-
tionally the $K^+$ mesons are observed to collectively move
out-of-plane (Fig. 3) as indicated by the negative $v_2$ val-
ues. In case of $K^-$ mesons (Fig. 2 and Fig. 3 right pan-
els), both $v_1$ and $v_2$ are compatible with zero within the
statistical sensitivity of the data, i.e. an isotropic emis-
sion pattern is observed.

The KaoS Collaboration has measured $v_2$ coefficients of
$K^\pm$ to be $v_2(K^+) = -0.05 \pm 0.03$ and $v_2(K^-) =
-0.09 \pm 0.06$ at mid-rapidity for the same collision system
at the same beam energy, however, with a different detec-
tor acceptance and collision centrality (3.8 < $b_{geo} < 6.5$
fm) [16]. The $v_2$ values from our data, reduced to the
same centrality range and acceptance, are compatible
with the KaoS results, but do not show any indication
for in-plane emission of $K^-$ mesons.

In order to link the flow measurements to the $K^\pm$
properties in the nuclear medium, a comparison to the
predictions of transport model calculations is necessary.
For this analysis we utilize the Hadron String Dynamics
(HSD) model [25] and Isospin Quantum Molecular Dy-
namics (IQMD) [26] offering a state-of-the-art descrip-
tion of kaon dynamics [4]. The models employ different
in-medium scenarios for the modification of strange par-
ticle properties in the dense and hot medium: in HSD
the chiral perturbation theory [27] for kaons and a cou-
pled channel G-matrix approach [28] for antikaons are
implemented. In IQMD transport approach the relativis-
tic mean-field model for kaons and antikaons based on a
chiral SU(3) model is used [29].

The centrality selection imposed on the data is realized
by weighting the events with an impact parameter depen-
dent function. This function is obtained by evaluating
the influence of a multiplicity selection on the impact
parameter distribution within the IQMD model which
describes the multiplicity distribution – after cluster for-
mation – reasonably well. Earlier data on flow of $K^\pm$
mesons [15] and the $K^0$ spectra in pion induced reactions
[30] were successfully described by HSD with a repulsive
$KN$ potential of $20 \pm 5$ MeV for particles at rest ($p = 0$),
at normal nuclear matter density and a linear depend-
ence on baryon density. Employing this parametriza-
tion for the $K^+N$ potential in both HSD and IQMD,
and a similar, but attractive one with $U_{K^-N}(p = p_0, p =
0) = -45$ MeV in IQMD and a G-Matrix formalism cor-
responding to $U_{K^-N}(p = p_0, p = 0) = -50$ MeV in HSD
for the $K^-N$ potential the model predictions depicted by
the full lines in Fig. 2 and Fig. 3 are obtained. The phase
space distributions obtained from the transport calcula-
tions are filtered for the detector acceptance. The flow
observables are calculated using the true reaction plane.
Typical statistical uncertainties in the calculations are of
the order $\Delta v_1 \approx 0.005$ and $\Delta v_2 \approx 0.01$. The effect of the
in-medium potentials is visible in the difference to the model calculations without in-medium potential (dashed lines) that still include $K^+N$ rescattering and absorption processes for $K^-$ mesons.

Inspection of Fig. 2 reveals that according to the transport models the largest sensitivity to the presence of in-medium potentials is achieved with the sideflow observable, $v_1$, near target rapidity. Without any in-medium modifications the $K^+$ mesons should be emitted nearly isotropic, i.e. $v_1$ and $v_2$ values are close to zero. The presence of a repulsive $K^+N$ potential manifests itself by pushing the $K^+$ mesons away from the protons, thus generating the ‘anti-flow’ signature of $K^+$ mesons. The magnitude of the ‘anti-flow’ is correctly described by IQMD transport approach with the assumption of a $K^+N$ potential of $20 \pm 5$ MeV, while HSD predicts the ‘anti-flow’ effect but quantitatively overestimates the magnitude of the experimentally observed ‘anti-flow’. For $K^-$ mesons the interpretation is different: because of the strong absorption due to strangeness exchange reactions with baryons, an ‘anti-flow’ signature is expected without the presence of a potential (Fig. 2). This is clearly disfavored by the data. Assuming an additional attraction of $K^-$ toward protons, due to strong interaction, the IQMD transport model predicts an almost isotropic emission pattern, as it is observed in the data. HSD predicts a strong ‘flow’ signature in the near target region, though. Following both model predictions the data indicate the presence of an attractive $K^-N$ potential. Following the IQMD approach, the depth of the potential can be constrained to $U_{K^-N}(\rho = \rho_0, p = 0) = -40 \pm 10$ MeV. The second harmonic $v_2$ of $K^+$ mesons (Fig. 3) shows a squeeze-out signature at mid-rapidity that is explained within the IQMD model by the presence of an in-medium potential. The HSD model predicts a weak squeeze-out effect, deviating by about $2 \Delta v_2$ from the data. Within the statistical sensitivity of the data this observable does not show any sensitivity to the potential away from mid-rapidity.

In the near target rapidity region the experimental $v_2$ is underestimated by both model calculations. However, the deviation is at the limit of the statistical significance. Note that also the $v_2$ values of protons (Fig. 3) are not reproduced by HSD. In the case of $K^-$ elliptic flow, experimental uncertainties are too large to draw any conclusion about the $K^-N$ potential.

To probe the consistency of the transport model description of the current data, shown in Fig. 2, we present in Fig. 4 the differential dependence of $v_1$ on the transverse momentum $p_T$ for $K^+$ mesons near target rapidity ($-1.3 < y_{(0)} < -0.5$) for the two centrality classes (p) and (c) defined in Table 1.

In the central event sample the data are compatible with both, HSD and IQMD, calculations employing the in-medium potential described above, in agreement to previously published FOPI results [13]. The IQMD calculations reproduce the transverse momentum dependence and the strength of the $v_1$ coefficient for low transverse momenta ($p_T < 0.4 \text{ GeV/c}$). This quality of IQMD is also observed for the peripheral event sample, where the data show a slightly stronger $p_T$ dependence as compared to the central case. Within HSD the transverse momentum dependence is strongly over-predicted leading to very large asymmetries at small $p_T$ that are excluded by the data.

The influence of the Coulomb interaction was studied within the HSD transport model by comparing the flow patterns of $K_0^+$ and $K^+$ mesons. Both members of the isospin doublet show a similar $p_T$ dependence of $v_1$, but in case of $K^+$ mesons the predicted ‘anti-flow’ is up to 12 % higher at low transverse momenta. This difference

![Figure 2: (color online) Rapidity dependence of $v_1$ for protons (left), $K^+$ (middle) and $K^-$ mesons (right), in comparison to HSD and IQMD with (‘w’) and without (‘wo’) in-medium potential. Error bars (boxes) denote statistical (systematic) uncertainties. The star symbols for $K^-$ mesons at mid-rapidity in the right panel are from the high statistics data in the range $p < 1.0 \text{ GeV/c}$ with $S/B > 5$.](image-url)
FIG. 3: (color online) Rapidity dependence of \(v_2\) for protons (left), \(K^+\) (middle) and \(K^-\) mesons (right), in comparison to HSD and IQMD transport model predictions. Lines and symbols as in Fig. 2.

FIG. 4: (color online) Transverse momentum \((p_T)\) dependence of \(v_1\) distributions for \(K^+\) mesons in peripheral (left panel) and central (right panel) collisions in comparison to HSD and IQMD predictions with (solid lines) and without (dashed lines) in-medium potentials.

is attributed to the additional repulsion due to electromagnetic interaction between \(K^+\) mesons and protons in the near target region. The long range influence of the Coulomb attraction/repulsion between kaons and nucleons of the projectile and target remnants was investigated with the SACA clusterization algorithm [31] which simulates the propagation of particles in the Coulomb field up to flight times of \(\sim 10,000\) fm/c. Statistically significant influence was found only for the very small momenta, beneath the detector acceptance. We conclude that most of the asymmetry is caused by the strong interaction and that \(v_1\) can constrain the depth of the \(KN\) potential.

IV. CONCLUSIONS

We have measured the azimuthal emission patterns of \(K^\pm\) mesons in heavy-ion collisions near the strangeness production threshold energies. In case of \(K^+\) mesons a weak in-plane 'anti-flow' with respect to protons and a slight 'squeeze-out' are observed. For \(K^-\) mesons, within large statistic uncertainties, isotropic emission pattern is observed. Despite the large uncertainties, the comparison to two independent predictions of HSD and IQMD without potential especially of the first Fourier coefficient implies the existence of a weakly attractive \(K^-N\) in-medium potential. Furthermore, the IQMD transport approach, which is able to reproduce the dynamics of nucleons and \(K^+\) mesons, suggests a \(K^-N\) in-medium potential of \(U_{K^-N} = -40 \pm 10\) MeV.

The theoretical modeling of the in-medium potentials, or more generally of the in-medium interactions, is reasonably well achieved within the IQMD transport approach as is demonstrated by the detailed comparison of the differential flow pattern of the \(K^+\) mesons. Within HSD, the description is not satisfactory yet. Nevertheless, the observed dependencies and sensitivities point to the feasibility to extract the strength of the in-medium potentials from a quantitative description of a complete set of flow data. More systematic data and theoretical efforts are clearly necessary to reach this important goal.

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