Investigation of In-Medium Hadron Properties by Azimuthal Emission Patterns of $K^+$ and $K^-$

Tae Im Kang∗ (for the FOPI Collaboration)

Heidelberg University

E-mail: kang@physi.uni-heidelberg.de

Modification of hadron properties in hot and dense nuclear matter is a topic of great interest. Kaons, which are produced in nucleus-nucleus collisions at sub-threshold energies at SIS in GSI, are very promising particles to investigate in-medium effects on hadrons. Azimuthal emission patterns of $K^+$ and $K^-$ mesons have been measured in Ni+Ni collisions with the FOPI spectrometer at beam kinetic energy of 1.91A GeV to investigate an in-medium potential in dense baryonic matter. The presented results show the different propagation patterns of $K^+$ and $K^-$ mesons inside the dense nuclear medium and indicate the existence of a kaon-nucleon potential, repulsive for $K^+$ and attractive for $K^-$ comparing to the predictions of theoretical model.

∗Speaker.
1. Introduction

Relativistic heavy-ion collisions at incident energies range of 1-2A GeV provide a unique opportunity to study both the properties of hadrons in dense nuclear matter and the behavior of nuclear matter at high densities [1]. The possible modification of hadron masses and widths in hot and dense matter is a subject of great current interest. In particular the investigations of the in-medium properties of kaons is important for understanding chiral symmetry restoration [2].

1.1 Kaons in dense nuclear matter

As a consequence of chiral symmetry restoration in hot and dense nuclear matter, the effective mass of charged kaons are expected to be modified with increasing baryon density. Various model calculations agree qualitatively on their predictions of the total energy of $K$ mesons at rest in nuclear matter as function of density [3]. According to the calculations, the effective mass of $K^+$ mesons increases moderately with increasing baryon density whereas the effective mass of $K^-$ mesons decreases significantly. Mean-field calculations predict this effect is caused by a repulsive $K^+$-nucleon potential and an attractive $K^-$-nucleon potential. This in-medium $K$-nucleon potential in dense hadronic matter is expected to manifest itself in their azimuthal emission pattern with respect to the reaction plane [4].

1.2 Azimuthal emission patterns

The phenomenon of collective flow [5] can generally be characterized in terms of anisotropies of the azimuthal emission pattern, expressed by a Fourier series:

$$\frac{dN}{d\phi} \propto (1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + ...),$$

(1.1)

where $\phi$ is the azimuthal angle of the outgoing particle with respect to the reaction plane [6]. The first order Fourier coefficient, $v_1 = \langle \cos(\phi) \rangle = \langle p_x/p_T \rangle$, describes the sideward deflection of particles in the reaction plane. The second order coefficient, $v_2 = \langle \cos(2\phi) \rangle = \langle (p_x/p_T)^2 - (p_y/p_T)^2 \rangle$, describes the in-plane/out-of-plane emission pattern with respect to the reaction plane.

2. FOPI ToF upgrade

The FOPI detector [7] is an azimuthally symmetric apparatus comprising several sub detectors (Fig 1, left panel) which provide charge and mass determination over nearly the full solid angle. The identification of charged particles is achieved by the curvature of particle tracks in the magnetic field, by their specific energy loss in the drift chamber, and by the time-of-flight (ToF). Recently FOPI has successfully upgraded the Time-of-Flight detector system with a barrel of Multi-strip Multi-gap Resistive Plate Counters (MMRPC) [8] to improve the charged kaon measurement, Fig. 2. The charged kaons are identified from two ToF systems, MMRPC ($30^\circ < \theta_{lab} < 55^\circ$) and Plastic Scintillator Barrel (Plastic, $55^\circ < \theta_{lab} < 110^\circ$), matched with Central Drift Chamber (CDC, $28^\circ < \theta_{lab} < 135^\circ$).
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3. Results

The FOPI experiment recorded $69 \times 10^6$ Ni+Ni collisions, corresponding to the most central 60% of the reaction cross section ($b_{\text{geo}} < 7$ fm using the sharp cutoff approximation). The events were centrality selected by imposing conditions on the baryon multiplicity (Mul); defining a central ($48 < \text{Mul} < 90$) and a peripheral event ($0 < \text{Mul} \leq 47$) classes. The corresponding geometrical impact parameter ($b_{\text{geo}}$) ranges are classified using a sharp cut-off approximation: $0 < b_{\text{geo}} < 3$ fm and $3 < b_{\text{geo}} < 7$ fm for a central and a peripheral event classes, respectively.

3.1 Particle identification of $K^+$ and $K^-$

In total, 233,300 $K^+$ mesons with a signal-to-background-ratio (S/B) better than 10 and 5,200 $K^-$ mesons with S/B better than 4 were identified in the interval of $\pm 2\sigma$ around the nominal kaon...
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mass from the Plastic and MMRPC mass spectra (Fig. 3).

3.2 The FOPI data of $v_1$ for $K^+$

In Fig. 4, earlier publications on $v_1$ of $K^+$ mesons (circle symbols) and protons (triangle symbols) are presented. The opposite sign of $v_1$ for $K^+$ mesons and protons at low $p_T$ demonstrate the existence of a repulsive potential in the dense nuclear medium.

The new experimental data, that presented here, on $v_1$ of $K^+$ are also shown in Fig. 4 as square symbols and compared to the old FOPI data (circle symbols) [9] with the same selection of collision centrality ($b_{geo} < 2.55 \text{ fm}$) and rapidity range ($-1.2 < y_0 < -0.65, y_0 = y_{lab}/y_{cm} - 1$). The new data are agreeing with the old FOPI data that were well described by the Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) model with a repulsive in-medium $K^+$-nucleon potential of $U = 20 \text{ MeV}$.

3.3 Centrality dependence of $v_1$ for $K^+$

To study the centrality dependence of $v_1$ for $K^+$, two impact parameter ranges, $3 < b_{geo} < 7 \text{ fm}$ (peripheral events) and $b_{geo} < 3 \text{ fm}$ (central events) near target rapidity ($-1.3 < y_0 < -0.5$) are evaluated in Fig. 5. Here there is a clear trend for positive $v_1$ at low $p_T$ and negative $v_1$ at high $p_T$. A change in the $v_1$ of $K^+$ pattern can be observed, from central to peripheral collisions. The systematic errors (boxes in Fig. 5) are estimated as 0.024 and 0.012 for peripheral and central collisions, respectively.

In order to evaluate the implications of the data in terms of the properties of $K^\pm$ in the dense nuclear medium, the data are compared to the predictions of Hadron String Dynamics (HSD) model [10] without and with an in-medium potential. The strength of the in-medium $K^+$-nucleon potential at normal nuclear density and zero momentum was implemented as $U = 20 \text{ MeV}$ because earlier publications on $v_1$ of $K^+$ [9] and the $K^0$ spectra [11] could successfully be described by HSD with an in-medium potential of $U = 20 \pm 5 \text{ MeV}$. Note that only sharp cutoff approximation method was used for the comparison between HSD and the data. However, the model calculations overestimate the magnitude of $v_1$ for $K^+$ at low $p_T$, especially for peripheral collisions in Fig. 5.

3.4 $v_1$ and $v_2$ of $K^+$ and $K^-$

The experimental data on $p_T$-integrated $v_1$ and $v_2$ for the full event sample ($b_{geo} < 7 \text{ fm}$) are presented as function of $y_0$ in Fig. 6. The upper left panel shows positive $v_1$ for $K^+$ whereas the values of $v_1$ for $K^-$ are compatible with zero within the sensitivity of the data as shown in the upper right panel. For a symmetric system, $v_1$ at mid-rapidity should be zero because $v_1$ should be antisymmetric with respect to mid-rapidity. This systematic errors (boxes in the upper left panel...
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**Figure 4:** The FOPI data of $v_1$ for $K^+$ mesons (circle symbols) and protons (triangle symbols) in the rapidity range $-1.2 < y_0 < -0.65$ for central ($b_{geo} < 2.55$ fm) Ni+Ni collisions at 1.93A GeV [9]. The preliminary data on $v_1$ of $K^+$ (square symbols) are added in the picture which was taken from [9].

**Figure 5:** $v_1$ of $K^+$ mesons (points) in peripheral (peri) and central (cent) collisions. The data are compared to the HSD calculations with (‘w’) and without (‘wo’) in-medium potential. The statistical uncertainty on the HSD calculations shown separately in the upper right side in the left panel.

of Fig. 6) are estimated as 0.020 from the mid-rapidity offset. The lower plots in Fig. 6 show that the $v_2$ values of $K^+$ are negative (preferential out-of-plane emission [6]), while those of $K^-$ are compatible with zero within the sensitivity of the data.

The data are compared to the HSD calculations with and without in-medium potential in Fig. 6. As mentioned above, the strength of an in-medium $K^+$-nucleon potential was implemented as $U(K^+) = 20$ MeV at normal nuclear matter density with a linear density dependence. A linear $K^-$-nucleon potential of $U(K^-) = -50$ MeV [12] was employed in the HSD model calculations based on theoretical expectations. With this choice of potential the model predicts that the $v_1$ values are close to zero without any in-medium potential. But when the finite repulsive in-medium potential is introduced, $K^+$ mesons are pushed away from protons and therefore $v_1$ values of $K^+$ are positive. The model calculations of $v_2$ for $K^+$ agree with the data reasonably well, but do not show a strong sensitivity for the in-medium potential.

For negative charged kaons, the model calculations predict that $K^-$ mesons are strongly absorbed by nucleons and thus show $v_1$ values of $K^-$ are positive without in-medium potential. However, the attractive in-medium potential pulls $K^-$ mesons towards nucleons and therefore $v_1$ turns from positive to negative. However, the depth of an in-medium potential in the model calculations need to be lowered compared to data. The model calculations of $v_2$ for $K^-$ show that the introduction of an attractive in-medium potential changes the sign of $v_2$ from negative (preferential
out-of-plane emission) to positive (preferential in-plane emission), but this effect cannot be verified with the presented data due to large statistical uncertainties.

4. Summary and outlook

In summary, we report on the measurement of the azimuthal emission patterns of $K^+$ and $K^-$ mesons in Ni+Ni collisions at 1.91A GeV. The data show the different propagation patterns of $K^+$ and $K^-$ mesons inside the hot and dense nuclear medium and indicate the existence of a kaon-nucleon potential compared to the HSD calculations. However, the origin of the discrepancy between the model calculations and data, especially for the peripheral collisions, has to be investigated in collaboration with theory groups. The measurement of azimuthal patterns of the $K^+$ and $K^-$ provides valuable information on an in-medium potential in the dense nuclear medium.

References