Abstract. Heavy ion collisions at SIS energies (1-2 AGeV) offer an unique tool to probe the properties of hot and dense nuclear matter. In particular, the partial restoration of chiral symmetry is predicted to lead in this energy range to in-medium modifications of hadron properties. Strange particle production below or close to the threshold energy is a useful probe to investigate these in-medium effects. The FOPI collaboration has recently measured the production and the propagation of charged and neutral strange particles. The \( K^+ \) production probability is investigated as a function of the system size at a beam energy of 1.5 AGeV. Results on \( K^0 \) production in Ru+Ru collisions at 1.69 AGeV are presented, as well as \( K^-/K^+ \) ratio as a function of rapidity. In addition, the sideward flow of charged and neutral strange particles has been measured. Results are compared to predictions of transport calculations (BUU and IQMD).

1. Introduction

For the last two decades, strangeness production has played a very important role in nuclear physics. Strangeness enhancement was proposed as a signature of the quark gluon plasma in the early 80’s [2]. At the same time, lots of efforts have been devoted to the investigation of hadron properties in a hot and dense medium, both on the theoretical and experimental side, leading to the dropping mass scenario [3].

Kaons are of particular interest due to the sensitivity of their properties and propagation to the state of the nuclear matter in which they have been produced. Their properties may reflect the spontaneous breaking of chiral symmetry and its restoration. Due to the presence of a repulsive kaon-nucleon potential and an attractive antikaon-nucleon potential, kaon and antikaon masses vary differently as a function of the nuclear matter density. The kaon mass increases with the density whereas the antikaon mass decreases. As a consequence, it becomes energetically more difficult to produce a kaon and easier to produce an antikaon in a dense medium. This property can be observed by measuring kaon and antikaon yields in heavy ion collisions and comparing the results to theoretical predictions. Strangeness exchange reactions such as \( K^-N \leftrightarrow \pi\Lambda \) seem to play an important role in kaon production and have therefore to be taken into account. The kaon-nucleon potential also influences kaon propagation which is measured in terms

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This contribution is organized as follows: the method and quality of particle identification with the FOPI detector is presented in the next section. Section 3 concerns strangeness production. $K^+$ production has been measured as a function of the system size. $K^+$ and $K^0$ rapidity distributions are presented as well as $K^-/K^+$ ratio. In section 4, results on the sideward flow of charged and neutral strange particles are summarized.

2. FOPI detector and particle identification

The FOPI detector [4], installed at SIS/GSI (Darmstadt) has a relatively large coverage of the phase space and is composed of several sub-detectors. The central part is placed in a solenoid providing a magnetic field of 0.6 T and consists of a drift chamber (CDC) and a barrel of plastic scintillators. The forward part consists of a second drift chamber (HELITRON) and a wall of plastic scintillators. The later provides a measurement of the charged particle multiplicity in the forward hemisphere, used for centrality selection.

The results presented in this contribution have been measured in the central part of the FOPI detector (CDC + BARREL). The measurement of the track curvature in CDC due to the magnetic field is combined with the energy loss of particles and provides a first mass identification (Bethe-Bloch) as well as a charge sign identification. A second mass identification is obtained when a track in the CDC can be matched to a hit in the BARREL that provides a time-of-flight measurement.

An upper momentum cut of 0.5 GeV/c is needed to properly separate charged kaons from pions and protons. A mass distribution is presented on figure 1 (left panel) for Ru+Ru collisions at 1.69 AGeV.

Neutral kaons and $\Lambda$ are reconstructed from their decay into $\pi^+ \pi^-$ and $p \pi^-$, respectively. Only the short component $K^0_S$ with a $c\tau$ of 2.68 cm can be measured in the
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FOPI detector, the $K^0_L$ decaying outside of the apparatus. Invariant mass spectra are shown on figure 1 for $K^0_L$ (middle panel) and $\Lambda$ (right panel). The dark area represents the combinatorial background obtained from event mixing.

The results presented in what follows have been corrected for matching and cut efficiencies using protons with the same momentum for $K^+$ corrections and a detailed GEANT-based simulation for neutral strange particles.

Figure 2 shows the acceptance for $K^+$ (left panel) and $K^0$ (right panel) in terms of transverse momentum as a function of rapidity. For charged kaons, the acceptance is limited by the polar angle coverage of the central barrel ($40^\circ < \theta_{\text{lab}} < 130^\circ$) and by the upper momentum cut of 0.5 GeV/c needed to properly identify kaons. In addition, a transverse momentum of at least 0.1 GeV/c is needed for the particles to reach the time-of-flight barrel. In the case of neutral particles, the acceptance is larger due to the kinematics of the decay and covers the whole backward hemisphere.

![Figure 2. Acceptance in terms of $p_t$ as a function of rapidity for $K^+$ (right) and $K^0$ (left). The rapidity is normalized to the beam rapidity.](image)

3. Strangeness production

As already mentioned, strangeness production is connected to fundamental aspects of nuclear physics and appears as a promising tool to probe the modification of hadron properties in-medium. However, those properties may depend as well on the nuclear equation of state. For this reason, it is necessary to perform systematic analysis of various systems and to compare those results to theoretical predictions. This has been investigated by the KaoS collaboration [5].
3.1. Dependence of $K^+$ production on the system size

The FOPI collaboration has recently investigated the $K^+$ production as a function of the system size at a beam energy of 1.5 AGeV. The number of charged kaons has been measured in the acceptance of the FOPI central part in central Ca+Ca, Ru+Ru and Au+Au collisions [6]. An older point for Ni+Ni collisions has been included [7]. Data are corrected for cut and matching efficiencies. Results are presented on figure 3 (squares). The calcium point has been obtained with a very poor statistics. A slight increase from the Ni system to the Au system is observed. This increase is predicted by transport calculations (BUU (Boltzmann-Uehling-Uhlenbeck) [8] and IQMD (Isospin Quantum Molecular Dynamic) [9]). The data seem to favor the version with in-medium effects for the IQMD model (open triangles). It is hard to draw any conclusion for the BUU model.

![Figure 3](image.png)

**Figure 3.** $K^+$ production as a function of the system size at a beam energy of 1.5 AGeV. Data are shown by the squares. Triangles (circles) show the predictions of the IQMD (BUU) model without (solid symbols) and with (open symbols) in-medium effects.

3.2. $K^+$ and $K^0$ rapidity distribution

Rapidity distributions are obtained by fitting transverse mass spectra in narrow rapidity windows by a Boltzmann function. The integral of the fit function between $m_0$ and $\infty$ gives the yield. Results for central Ru+Ru collisions at 1.69 AGeV are presented on figure 4. $K^+$ ($K^0$) data are shown by the squares (dots). $K^0$ yields have been multiplied by a factor of 2 to account for the $K^0_L$ component that is not measured with...
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Our apparatus. Charged and neutral kaon yields agree with each other within error bars. Solid (dashed) lines show the results of transport calculations without (with) in-medium effects for BUU (thin lines) and IQMD (thick lines). The largest effect appears in the mid-rapidity region where the densities are the highest. This shows the importance of measuring strangeness production close to mid-rapidity. For the first time, the FOPI collaboration presents kaon data in this region of phase space.

The IQMD model overestimates the data with the two different scenarios whereas the version of BUU without in-medium effects agrees with the data over the whole rapidity range.

The differences between the models is due to different elementary cross sections used as input. It has been checked that the same cross sections lead to the same results with both models [10].

\[
\begin{align*}
\text{measured} & \quad \text{reflected} \\
\text{w/o IME} & \quad \text{w IME}
\end{align*}
\]

Figure 4. Rapidity distributions for \(K^+\) (squares) and \(K^0\) (dots) in Ru+Ru collisions at 1.69 AGeV. The thick lines show the IQMD predictions and the thin lines show the BUU calculations without (solid lines) and with (dashed lines) in-medium effects.

3.3. \(K^-/K^+\) ratio

The FOPI collaboration has also investigated the \(K^-/K^+\) ratio as a function of rapidity in Ru+Ru collisions at 1.69 AGeV and Ni+Ni collisions at 1.93 AGeV [11]. Results are presented on figure 5 for central collisions. Experimental data are shown by the dots. The ratio increases from target rapidity to mid-rapidity reflecting the fact that the kaon production in a dense medium is reduced due to the repulsive potential whereas the antikaon production is enhanced due to the presence of an attractive antikaon-nucleon potential.
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Data are compared to the predictions of the BUU model without in-medium effects (solid line) and with two different K$^-$ potentials (dotted and dashed lines). The version without in-medium modifications of kaon masses fails to reproduce the trend observed in the data. The calculations including in-medium potential show the same trend as the experimental data, which seem to favor the smaller antikaon potential. This corresponds to a K$^-$ mass reduction by 12% at normal nuclear matter density.

![Figure 5](image)

**Figure 5.** K$^-$/K$^+$ ratio as a function of the rapidity for Ru+Ru collisions at 1.69 AGeV (left panel) and Ni+Ni collisions at 1.93 AGeV. Data are shown by the dots. The shaded area shows an estimate for systematic errors. The solid lines show BUU calculations without in-medium effects. The dotted (dashed) lines correspond to $U_{K^+} = 30$ MeV and $U_{K^-} = -120$ MeV (-70 MeV).

4. Strangeness propagation

The differential sideward flow of strange particles is presented on figure 6 for Ru+Ru central and semi-central collisions at 1.69 AGeV in terms of the first Fourier coefficient ($v_1 = \langle \cos(\phi) \rangle$ where $\phi$ is the angle between the particle and the reaction plane) as a function of the transverse momentum. The upper panel shows the results for K$^+$ (dots) and protons (triangles). The kaon sideward flow varies with the transverse momentum from positive values of $v_1$ to negative values. The shaded area shows the BUU calculations for protons. The dotted line shows BUU calculations without in-medium effects. The solid and dashed lines show the calculations for two potentials. The kaon data clearly favor the versions with in-medium potential. Note that the sensitivity to in-medium effects is the largest at low transverse momenta.
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Figure 6. First Fourier coefficient as a function of transverse momentum in Ru+Ru semi-central (left) and central (right) collisions at 1.69 AGeV. Upper panel: K\(^+\) (dots) and protons (triangles) compared to the predictions of the BUU model (shaded area: protons, dotted line: without potential, dashed line: \(U=15\) MeV, solid line: \(U=20\) MeV). Middle panel: \(\Lambda\) (squares) and protons (triangles). Lower panel: K\(^+\) (squares) and K\(^0\) (circles).

The middle panel shows results for \(\Lambda\) (open squares) compared to protons (open triangles) [12]. Although \(\Lambda\) are produced with the same mechanism as K\(^+\), their flow pattern is very different. Their flow follows the one of the protons although the magnitude is a little lower.

Results for K\(^0\) (open circles) [12] are compared to K\(^+\) flow (squares) in the lower
panel. Within error bars, neutral kaon flow is compatible with charged kaon flow which evidences a very weak effect of the Coulomb potential.

5. Summary

The FOPI collaboration has measured strangeness production and propagation in nuclear matter at SIS energies. Results on K\(^+\) and K\(^0\) rapidity distributions as well as K\(^-\)/K\(^+\) ratio in Ru+Ru collisions at 1.69 AGeV have been presented. The differential sideward flow of K\(^+\), K\(^0\) and \(\Lambda\) has been measured in Ru+Ru collisions at 1.69 AGeV and Ni+Ni collisions at 1.93 AGeV.

Experimental data are compared to the predictions of transport model calculations (BUU and IQMD). Although the set of available data is quite large, it is still not possible to draw definitive conclusions on the presence of in-medium modifications of hadron properties. Some observables, like rapidity distributions, seem to favor a scenario where kaon masses are not modified in-medium whereas others, like the flow, favor calculations including in-medium modification of hadron masses. It appears that none of the models used in this work is able to reproduce all observables with one set of parameters.

References

[1] J. Rafelski and B. Müller 1982 *Phys. Rev. Lett.* 48 1066
[2] G.E. Brown and M. Rho 1991 *Phys. Rev. Lett.* 66 2720
[3] P. Crochet *et al.* (FOPI collaboration) 2000 *Phys. Lett.* 486 6
[4] A. Gobbi *et al.* (FOPI collaboration) 1993 *Nucl. Inst. Meth.* A324 156
[5] C. Sturm *et al.* (KaoS collaboration) 2001 *Phys. Rev. Lett.* 86 39
[6] A. Devismes 2001, PhD Thesis, University of Technology, Darmstadt, Germany
[7] D. Best *et al.* (FOPI collaboration) 1997 *Nucl. Phys.* A625 307
[8] W. Cassing and E.L. Bratkovskaya 1999 *Phys. Rep.* 308
[9] Ch. Hartnack 1992, PhD Thesis, University of Frankfurt, Germany
[10] Ch. Hartnack 2001, these proceedings
[11] K. Wiśniewski *et al.* (FOPI collaboration) 2000 *Eur. Phys. J.* A9 515
[12] R. Kutsche 2000, PhD Thesis, University of Technology, Darmstadt, Germany