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Abstract

Experimental data on K^+ and proton sideward flow measured with the FOPI detector at SIS/GSI in the reactions Ru + Ru at 1.69A GeV and Ni + Ni at 1.93A GeV are presented. The K^+ sideward flow is found to be anti-correlated (correlated) with the one of protons at low (high) transverse momenta. When compared to the predictions of a transport model, the data favour the existence of an in-medium repulsive K^+-nucleon potential.

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The possible modification of hadron masses, widths and dispersion relations in hot and dense matter is a subject of considerable current interest. In particular a large theoretical effort has been devoted to the investigations of the in-medium properties of kaons as they are important for understanding both chiral symmetry restoration and neutron star properties [1]. These studies, carried out using different approaches [2], converge qualitatively towards the common feature that in the nuclear medium the K^+ feels a week repulsive potential whereas the K^- feels a strong attractive potential. Both potentials vary almost linearly with the nuclear density up to 2 ρ_0. Experimentally, the in-medium kaon properties at low densities can be studied by the analysis of kaon-nucleus scattering [3] and kaonic atoms [4] data. The high density kaon properties can only be investigated by means of heavy ion collisions. This is particularly relevant for beam energies of 1-2A GeV for which, according to transport model calculations [5], the central region of the collision reaches nuclear densities of 2-3 times the normal nuclear density and stays in this high density phase for a relatively long time. This beam energy range is also best suited to study the kaon in-medium properties since it corresponds to kaon production below threshold or close-to-threshold [1]. As the kaon in-medium potential results in a slightly increased K^+ mass and a strongly reduced K^- mass, one expects to observe an enhanced K^- yield (its production being energetically much easier) and a reduced K^+ yield (its production being energetically more difficult). The large K^- production cross-section observed by the KaoS collaboration in Ni+Ni collisions has been interpreted as an evidence for a reduced K^- effective mass in the nuclear medium [6]. On the other hand the kaon potential should repel K^+ from nucleons and attract K^- towards nucleons. This would influence the phase space populations by a widening (narrowing) of the K^+ (K^-) transverse momentum and rapidity distributions. First signs of these effects have been observed very recently by the KaoS and the FOPI collaborations [7,8]. Finally, the collective flow of kaons, both the in-plane component (the scope of this paper) and the out-of-plane component [9], are also recognized as relevant observables to probe the kaon potential and thus provides useful complementary information [10]. The first experimental data on K^+ sideward flow have been obtained by the FOPI collaboration in Ni+Ni reactions at 1.93A GeV [11]. The data show a vanishing K^+ flow in the representation of the mean in-plane transverse momentum *versus* rapidity. The sensitivity of such data to in-medium effects is under intense debate. According to [12] the data clearly support the existence of a repulsive K^+-nucleon mean field. According to [13,14] the sensitivity of the observable to in-medium effects is found to be less pronounced but a slightly repulsive potential cannot be excluded from the comparison. On the other hand, the sensitivity of K^+ sideward flow to in-medium effects was found in [15] to be washed-out when a particular momentum dependence of the potential is included in the calculations. At last, it was recently pointed-out in [16] that the lifetime of nuclear resonances used in the models might be partially responsible for the magnitude of the K^+ sideward flow as it is a crucial ingredient for kaon production channels.

In order to further elucidate these questions, we investigate in this paper the transverse momentum dependence of the K^+ and the proton sideward flow in both the Ru+Ru and the Ni+Ni system. Such a transverse momentum differential analysis does reveal more information compared to the transverse momentum integrated data where part of the effects are hidden. In addition, using a heavier system than Ni+Ni is better suited for flow studies since flow effects are found to be larger, at least for baryons, as compared to lighter systems [17]. It allows also to study K^+ flow in non-central collisions where, due to a large sensitivity of the observable to in-medium effects, an *anti-flow* phenomenon (see later) is expected to be seen [12,18].

The FOPI detector [19] is an azimuthally symmetric apparatus made of several sub-detectors which provide charge and mass determination over nearly the full 4π solid angle. For the analysis presented here, only the Central Drift Chamber (CDC), the time of flight array (Barrel) and the forward Plastic Wall (PLA) were used. The CDC and the Barrel are placed in a solenoidal magnetic field of 0.6 T. Pions, kaons, protons, deuterons and tritons are identified with the CDC ($33° < \theta_{\mathrm{lab}} < 150°$) by means of the relation of the energy loss and the magnetic rigidity. Due to the low kaon yield in this beam energy regime, additional redundancy for kaon identification is needed. This is achieved by adding to the previous informations the particle velocity which is determined from the extrapolation of a track in the CDC to the appropriate hit in the Barrel. The acceptance is therefore reduced for kaons to the geometrical coverage of the Barrel : $39° < \theta_{\rm lab} < 130°$. Kaon detection is possible only for transverse momenta above $p_t = 0.1$ GeV/c which is needed for a particle to reach the Barrel. The upper momentum limit to which K^+ can be identified without significant contamination from pions and protons is $p_{\rm lab} = 0.5$ GeV/c. More details about kaon identification with the FOPI detector can be found in [8,11,20].

The acceptance of the FOPI detector for K^+ identification is shown in Fig. 1 in terms of K^+ transverse momentum as a function of the normalized rapidity $y^{(0)}$ where $y^{(0)}$ denotes the particle rapidity divided by the beam rapidity in the center-of-mass (c.m.) system. With this normalization, -1,0 and 1 correspond to target, c.m. and projectile rapidity, respectively.

The events were centrality selected by imposing cuts on the multiplicity PMUL [21] of charged particles detected in the outer part of Plastic Wall ($7° < \theta_{\rm lab} < 30°$). For the Ni+Ni system, one class of central events was selected by requiring PMUL≥40. For the Ru+Ru system, two different event classes were considered. The first one, defined by 40≤PMUL≤50 corresponds to the more peripheral events accessible with the hardware triggers. A more central set of events was selected by requiring PMUL≥52. The features of these event classes are listed in Table I. The reaction plane was reconstructed event-wise, according to the method devised in [22]. In order to remove autocorrelation effects, the azimuth of the reaction plane was estimated for each particle in a given event using all detected baryons in the event except the particle of interest. The flow observable presented here was corrected for the accuracy with which the reaction plane was determined, according to the method described in [23]. The corresponding correction factors f are shown in Table I.

The p_t dependence of the sideward flow has been investigated by means of a Fourier expansion of azimuthal distributions. ϕ being the azimuthal angle of a particle with respect to the reaction plane, the azimuthal distributions $dN/d\phi$ can be parametrized by $\sim (1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + ...)$, where $v_n =< \cos(n\phi) >$ are the Fourier coefficients. Sideward flow is related to the first Fourier coefficient by : $v_1 =< \cos(\phi) >=< p_x/p_t >$ where p_x is the transverse momentum projected onto the reaction plane (for more details, see [24,25].) In order to get rid of non-trivial distortions introduced by the detector acceptance for K^+, v_1 was extracted in a portion of phase space free of any geometrical cuts. From Fig. 1 it can be seen that requiring $-1.2 < y^{(0)} < -0.5$ defines the p_t window $0.1 \lesssim p_t \lesssim 0.5$ GeV/c where v_1 can be extracted without severe acceptance effects for both systems. Note that the p_t range extends to much higher values for protons.

The magnitude of the K^+ sideward flow signal was found to depend somewhat on the mass window used to select K^+ candidates and the applied quality criteria for the tracks in the CDC and their matching with the Barrel detector. Therefore, systematical uncertainties were estimated by adding quadratically the errors estimated by comparing the flow values obtained with "strong" and "open" selection criteria on both the two previous quantities. The boundaries of these cuts were established from the apparatus resolution on the one hand, and from the degree of contamination of K^+ by other particles on the other hand. These systematical errors are smaller than the size of the symbols used in the following figures. Other possible sources of systematical errors have been investigated for the Ru+Ru system by means of Monte-Carlo simulations using the GEANT package [26]. This consists in a complete simulation of the FOPI apparatus including resolutions in energy deposition and spatial position, front-end electronic processing, hit reconstruction, hit tracking and track matching between the sub-detectors. The output of GEANT was analyzed in the same way as the experimental data and then compared to the input of the simulation. The results of the full simulation overestimate v_1 by few percent in the region of the phase space under consideration. This systematical effect was found to be *i)* independent of p_t, *ii)* slightly more pronounced in semi-central collisions than in central collisions and *iii)* almost negligible for protons. It is attributed to a loss of particles in the azimuthal region of the high track density of the reactions. Based on these simulations, the data points in Fig. 3 have been shifted-down by the offset S reported in Table. I. Since no signs of such systematical bias have been observed in the Ni+Ni system, for which the track density is significantly lower, no correction has been applied to the data for this system.

The K^+ and proton sideward flow is shown in Fig. 2 for the Ni+Ni system. It can be seen that the K^+ flow pattern is totally different than the one of protons. Protons have a negative v_1 for all p_t. Since the rapidity window used is located in the backward hemisphere, this means that protons are positively flowing whatever their p_t (for symmetry reasons v_1 has to be equal to 0 at $p_t = 0$). In contrast, K^+ have positive (negative) v_1 for low (high) p_t. In other words, K^+ are negatively flowing (or anti-flowing) at low p_t and positively flowing at high p_t. We stress that vanishing K^+ flow was seen, if p_t-integrated data were used [11]. This demonstrates the need to study flow effects simultaneously in a p_t-integrated and p_t-differential way. Doing so is of particular importance for what concerns the comparison between model predictions and experimental data, the latter being usually measured in a restricted p_t domain due to the finite acceptance of the detectors.

The centrality dependence of v_1 in the Ru+Ru system is shown in Fig. 3. A change in the K^+ flow pattern can be observed, from central to semi-central collisions. Note also the change in the proton flow pattern and in the difference between the K^+ and the proton signals. It has been shown in [27], that in data averaged over p_t no K^+ flow is seen in central Ru+Ru reactions, while some antiflow is observed in semi-central events. A similar anti-flow pattern has been observed very recently for K^0_S in Au+Au collisions at 6A GeV [28].

In order to demonstrate the sensitivity of the experimental findings to the properties of kaons in dense hadronic matter, the data were compared to the predictions of two different realisations of the Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU) model [18] : without and with in-medium effects. The first situation corresponds to a calculation including binary collisions plus potentials except kaon potentials. In the second scenario in-medium effects are taken into account. They are introduced by means of a dispersion relation from which kaon effective potentials and masses are derived. This results, for K^+, in an increased effective mass and a repulsive potential. The former tends to lower the K^+ production probability in a first chance nucleon-nucleon collision while the latter tends to push K^+ away from nucleons. The strength of the in-medium K^+ potential at normal nuclear density was fixed to U = 15 MeV and 20 MeV for the Ru+Ru system and to U = 20 MeV for the Ni+Ni system. More details about the calculations can be found in [13,18]. The centrality selection criteria imposed on the data described above was modeled by an impact parameter selection of the RBUU events requesting the same geometrical cross section. No detector filter was applied on the calculations since the region of phase space defined with the previously discussed rapidity window is, with the exception of both p_t edges, free of any detector bias. The K^+ decay losses are not taken into account since they have been found to lead to a negligible effect on v_1.

The results of the calculations are shown by the curves in Fig. 2 and 3. It can be observed that without in-medium K^+ potential the calculation fails to describe the low-p_t K^+ anti-flow phenomenon observed in the data. In contrast, when in-medium effects are taken into account the model reproduces very nicely K^- experimental signals for both systems. The additional repulsive potential pushes K^+ further away from nucleons therefore resulting in an anti-correlation between the K^+ flow and the proton flow. It is important to mention that neither rescattering effects nor the coulomb repulsion can explain satisfactorily the experimental behaviour of K^+ flow, since both of them are included in the two calculations. Furthermore rescattering of K^+ with nucleons is expected to increase slightly the K^+ sideward flow in the direction of nucleons [12], and coulomb potential is found to play an almost negligible role on K^+ sideward flow [14].

The results obtained here are in good qualitative agreement with the predictions of another independent transport model calculation including similar in-medium effects [12]. In addition, it has been shown that these two calculations give a consistent description of the measured K^-/K^+ ratio, for the same reactions, only if in-medium effects are taken into account [8,18,29]. From the inspection of Fig. 3, it can be seen that, in the framework of the considered model, although the present data favour the existence of the K^+ potential, they are not accurate enough to make a precise quantitative statement about the strength of this potential at normal nuclear matter density within less than 5 MeV.

On the other hand, the model fails in consistently describing the proton sideward-flow data in the considered target rapidity region, although a reasonable agreement is found in the mid-rapidity region [27]. This discrepancy is mostly due to an improper separation of free protons and bound nucleons in the target spectator which seems to be general problem of transport model calculations [30]. A similar discrepancy has indeed been observed from the comparison of experimental data and the predictions of the Relativistic Quantum Molecular Dynamics model in Au+Au reactions at 11A GeV [31]. This shows that more definite interpretation of the p_t-differential flow data for nucleon needs further detailed investigations.

In summary the transverse momentum and centrality dependence of K^+ and proton sideward flow in Ni+Ni and Ru+Ru collisions at SIS energies have been studied with the FOPI detector. The data reveal a K^+ anti-flow phenomenon originating mostly from low p_t K^+. The comparison of the data with the predictions of a transport model investigating in-medium kaon properties clearly favour the existence of an in-medium repulsive potential for K^+. The study of K^- flow, for which in-medium effects are expected to be more pronounced, should shed more light on this issue.

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TABLES

TABLE I. Mean geometrical impact parameter ($b_{\rm geom}$), correction factor (f) and offset (S) to sideward flow observables for the selected classes of events (see text). $b_{\rm geom}$ was calculated assuming a sharp cut-off approximation.

System	Ni+Ni	Ru+Ru	Ru+Ru
Centrality	40≤PMUL	40≤PMUL≤50	52≤PMUL
$b_{\rm geom}$ (fm)	1.7	3.8	2.3
f	1.48	1.18	1.28
$S_{\rm proton}$	0.	0.02	0.01
$S_{\rm K^+}$	0.	0.04	0.03

FIGURES

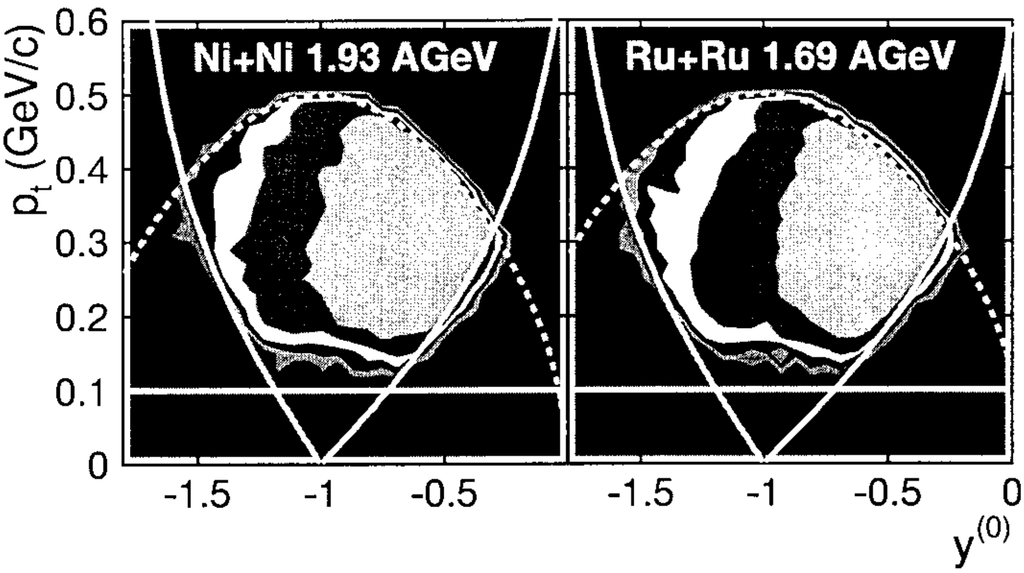

FIG. 1. Transverse momentum p_t *versus* normalized rapidity $y^{(0)}$ for identified K^+ in the reactions Ni+Ni at 1.93*A* GeV (left) and Ru+Ru at 1.69*A* GeV (right). The contour levels correspond to logarithmically increasing intensity. The solid curves denote the geometrical limits of the detector acceptance ($\theta_{\rm lab} = 39°$ and $130°$). The dashed curve corresponds to $p_{\rm lab} = 0.5$ GeV/c. The solid horizontal line corresponds to $p_t = 0.1$ GeV/c.

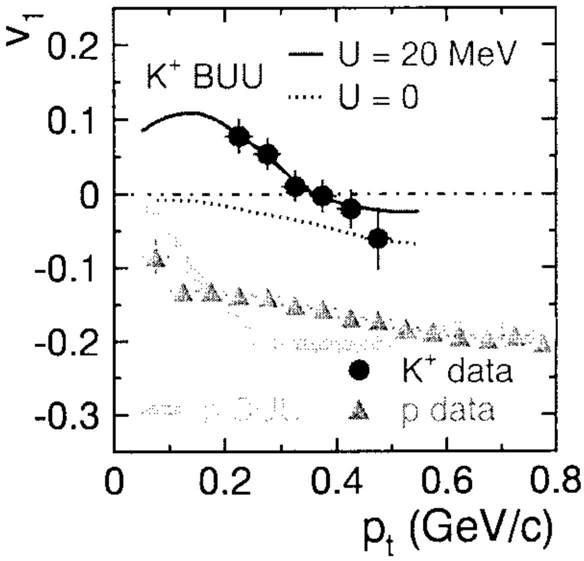

FIG. 2. v_1 *versus* p_t for protons (triangles) and K^+ (dots) in the rapidity range -1.2< $y^{(0)}$ <-0.5 for central Ni+Ni reactions at 1.93*A* GeV. Error bars represent statistical uncertainties. The curves and shaded area show the predictions of the RBUU model for K^+ and proton, respectively. The statistical uncertainties on RBUU-K^+ flow are similar to the ones on RBUU-proton flow. The latter are represented by the width of the shaded area.

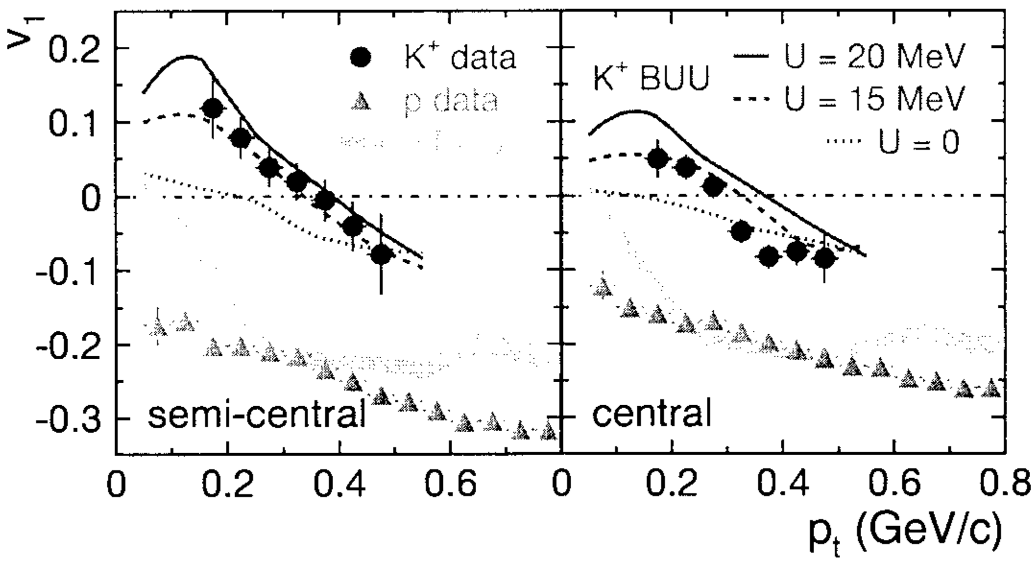

FIG. 3. Same as Fig. 2 for semi-central (left) and central (right) Ru+Ru reactions at 1.69A GeV.