

Strangeness production in heavy-ion collisions around 2A GeV in FOPI

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Abstract. Recent FOPI data on strangeness production in central Al+Al and Ni+Ni collisions at 1.9A GeV are presented, including yields of K^0 , Λ , strange resonances $\Sigma^{*\pm}(1385)$ and $K^{*0}(892)$, and results of searches for kaonic bound states in the Λp -channel. An emphasis is put on the findings on directed flow of charged kaons as well as comparison of ratios of integrated yields to the statistical model calculations.

1. Introduction

One of the central questions of the investigation of strangeness at beam energies of about 2A GeV is the issue of modifications of in-medium properties of strange hadrons in dense baryonic matter [1]. The production cross-section in the sub- and near-threshold energy domain is predicted to be influenced by the existence of the kaon-nucleon potential (U_{KN}) [2, 3]. The kaon flow was found to be sensitive to this potential. A relatively small positive value of $U_{KN} = 20$ MeV was extracted by comparing the RBUU model [4] prediction to the directed flow of K^+ measured by the FOPI Collaboration as a function of transverse momentum (p_T) integrated in specific ranges of rapidity and impact parameter. The attractive nature of the antikaon-nucleon interactions also leads to the prediction of antikaonic bound states in heavy-ion collision [5, 6]. In this paper the recent FOPI findings on strangeness production are reviewed.

2. MMRPC in FOPI: Enhancement of acceptance of the kaon phase space

For the detailed description of performances and measurement principles of FOPI apparatus the reader is referred to [7, 8]. In order to enhance the charged kaon identification capabilities in the momentum space, the Multi-strip Multi-gap Resistive Plate Chamber (MMRPC) Barrel [9] has been developed and installed at angles between 38° and 68° with respect to the nominal target position in the FOPI setup. The outstanding timing capabilities ($\sigma_\tau \lesssim 88$ ps) allow for almost unambiguous identification of K^+ up to momentum of 1.1 GeV/c and K^- up to 0.8 GeV/c (see Fig. 1), enabling the exploration of the abovementioned physics effects to a remarkably larger extent. In particular the kaon flow has been looked at in regions of rapidity (and impact parameters) not investigated before (see Sect. 4). For the detailed description of this detector's properties and performances, the reader is referred to [9].

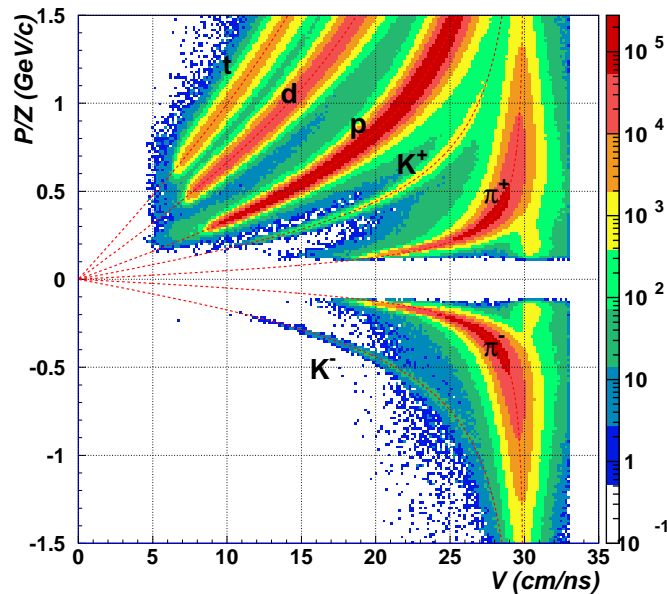


Figure 1. Momentum-velocity particle identification plot for the tracks matched with hits in the MMRPC Barrel timing detector.

3. Yields of particles containing strange quarks

The FOPI Collaboration has analysed a vast data sample on strangeness production from Al+Al and Ni+Ni central collisions at 1.9A GeV. The phase space distributions of about 33000 K_S^0 and 61000 Λ neutral strange particles have been reconstructed [10]. The emission patterns have been found to be in agreement with the simple Boltzmann model of emission from thermalized source, unlike for the case of protons. As the elongated rapidity distributions of bulk of charged baryons have been interpreted as indication of partial transparency of colliding matter [11], the differences in rapidity patterns of Λ and protons point to the different dynamics of pre-existing matter and the one created during the collision.

Emission of strange resonances like $\Sigma^{*\pm}(1385)$ and $K^{*0}(892)$ during the collision has been confirmed by the FOPI collaboration (cf. [12, 13]). In particular, production of Σ^* resonance aroused a considerable interest on the theory side, as it was predicted to play an important role in the antikaon production process via the $\pi\Lambda \rightarrow \bar{K}N$ channel in the nuclear medium. The abovementioned particles were investigated in their dominant decay channels ($\Sigma^* \rightarrow \Lambda + \pi^\pm$, $\Lambda \rightarrow p + \pi^-$ and $K^* \rightarrow K^+ + \pi^-$). Due to their short lifetimes ($\tau_{\Sigma^*} = 5$ fm/c, $\tau_{K^*} = 4$ fm/c), the decay products are experimentally indistinguishable from abundant emission of particles building up the background. Nevertheless, about 3100 ± 500 and 6100 ± 850 were identified on a significance level of about 9-10 and the masses found were in a good agreement with the values given in the Particle Physics Booklet [14]. Freeze-out yields of Σ^* and K^* were related to the emission rates of other identified particles and found to be: $P(\Sigma^*)/P(\Lambda + \Sigma^0) = 0.125 \pm 0.042$ and $P(K^{*0})/P(K^0) = 0.032 \pm 0.012$.

FOPI has been carrying out an extensive search for antikaonic bound states. Recently an intriguing signal has been found in the Λ -proton channel for both Al+Al and Ni+Ni collisions at 1.9A GeV, see Fig. 5 in ref. [15]. This excess over the combinatorial background is located at the invariant mass of $2.13 \text{ GeV}/c^2$, and characterized by the significance of 5 ± 1.4 . FOPI has also found no evidence for a signal located between 2.2 and $2.3 \text{ GeV}/c^2$, where a (ppK^-) -candidate

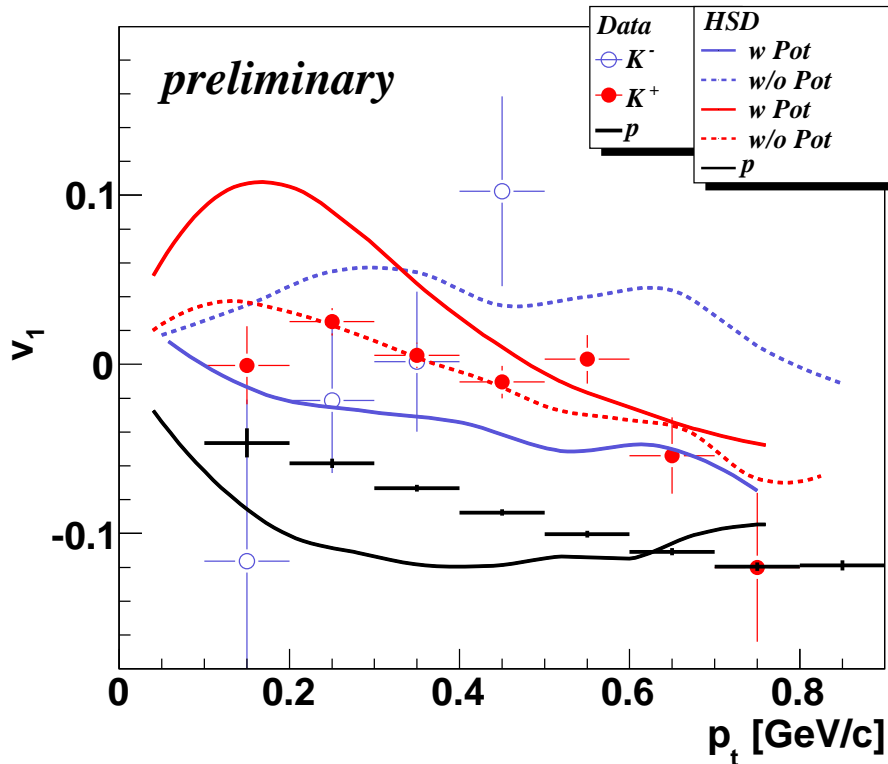


Figure 2. Directed flow of K^+ (full red points), K^- (open blue points) and protons (black points) as function of transverse momentum for $-0.6 < y^{(0)} < -0.2$ and $1.6 < b < 4.9$ fm. v_1 profiles obtained in the framework of the HSD model are marked as follows: solid (dotted) lines correspond to calculations with (without) potential. Blue (red, black) lines correspond to K^+ (K^- , p).

has been seen by the FINUDA collaboration [16], although at different colliding systems and beam energy. An interesting candidate for the explanation of the signal found by FOPI might be the $H1^+$ strange di-baryonic state with the energy exactly at the ΣN threshold in the elementary particle reactions.

ϕ mesons have been also measured by the FOPI Collaboration. The ongoing analysis of these particles emitted from Al+Al collisions has been reported in [17].

4. Directed flow of kaons

Directed flow of charged kaons emitted from Ni+Ni collisions at a beam energy of 1.9A GeV has been analysed for different regions of a phase space and collision centrality and compared to the predictions of the RBUU and HSD [4, 20] transport models. Our previous analysis has shown that K^+ sampled within $-1.2 < y^{(0)} < -0.65$ and $b > 1.7$ fm, where $y^{(0)} = y/y_{CM} - 1$ is the scaled rapidity, exhibit a relatively small positive v_1 , although dropping with p_T [18]. The RBUU predictions have been found to follow the experimental data if a small positive kaon-nucleon potential was introduced ($U_{KN} \approx 20$ MeV at density ρ equal to normal nuclear density ρ_0 , in a parametrization of a linear rise of U_{KN} with ρ). New data on the same colliding system and energy acquired with the newly-installed MMRPC Barrel fully confirmed the previous finding. In addition, the directed flow of K^+ and K^- has been analysed for a wider range of rapidity

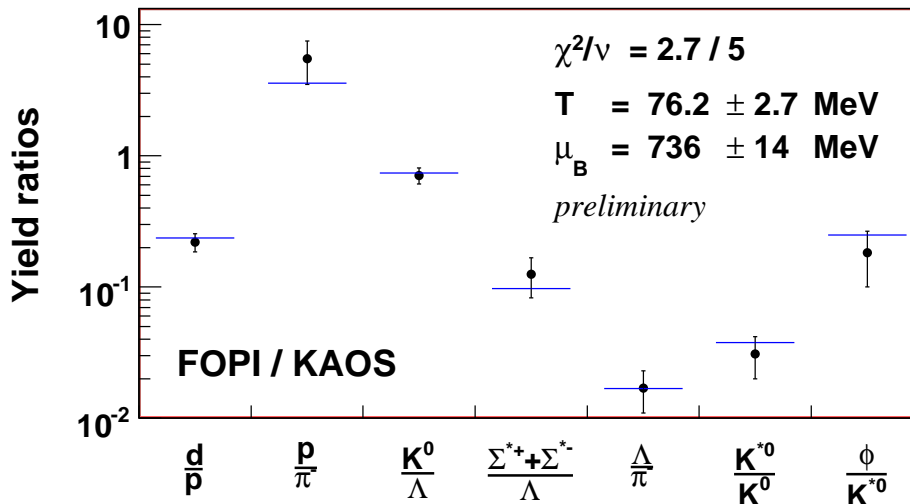


Figure 3. Ratios of particle yields for Al+Al collisions at 1.9A GeV, compared to the predictions of the Statistical Model (see text).

and impact parameter bins. Interestingly, for the v_1 pattern of K^+ within $-0.6 < y^{(0)} < -0.2$ and a charged hit multiplicity corresponding to $1.6 < b \text{ (fm)} < 4.9$ in a sharp cut-off model, shown on Fig. 2, the current HSD calculations [21] favour a vanishing U_{KN} potential in contrast to the need of a 20 MeV potential at backward rapidities. The data points on flow of K^- are characterized by considerably larger errors due to lower statistics mainly resulting from the freeze-out yield ratio $P(K^-)/P(K^+) \sim 0.03$ [19]. Here, the v_1 profiles obtained in the framework of the HSD model fail to follow the experimental trend for both $U_{KN} = 0$ and 20 MeV. The systematic error associated to v_1 have been estimated to be less than 0.01. We hope that this intriguing discrepancy in the patterns of the kaonic flow between the experiment and theory gives the chance for further theoretical refinements.

5. Comparison of integrated yields to the Statistical Model

Currently FOPI has obtained 7 ratios of integrated yields of p, d, π^- and particles containing strange quarks: K^0 , Λ^0 , Σ^{*0} , K^{*0} and ϕ emitted from Ni+Ni collisions at 1.91A GeV. For constructing the ratios, yields of unstable particles found in their decay channels were compared to ones of their respective decay products in order to minimize the experimental systematic errors. The Statistical Model (SM) predictions [22] were fitted with help of the THERMUS code [23] to the constructed array of yield ratios, as shown in Fig. 3. Calculations were performed in the framework of the canonical ensemble for particles containing non-zero strangeness and the grand canonical ensemble for the other hadrons. The model fits best to the data for a temperature of $T = 76.2 \pm 2.7$ MeV and a baryo-chemical potential of $\mu_b = 736 \pm 14$ MeV. Despite the simplifying condition of chemical equilibrium, SM delivers a good fit to all the yield ratios. The found parameters of T and μ_b are well in line with the observed trend on the phase diagram (cf. Fig. 11 in [24]).

6. Conclusions

The FOPI Collaboration has obtained a wide range of new data on strangeness production which may enhance understanding of the properties of strange particles in dense baryonic matter. Comparison of $v_1(p_t)$ for K^+ analysed in the new ranges of rapidity and impact parameter to the

prediction of HSD transport model favour a vanishing U_{KN} potential. For K^- , the divergence of trends between the experimental data and HSD prediction seems to be more pronounced, and the interpretation of these effects is still pending. The ratios of integrated yields from Al+Al collisions can be surprisingly well described by the Statistical Model with parameters of temperature and baryo-chemical potential well in line with other experimental freeze-out data.

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