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Production of Charged Kaons in Proton-Nucleus and Nucleus-Nucleus Collisions at 200 GeV/Nucleon

NA-35 Collaboration

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Abstract

Production of charged kaons in proton-sulphur, proton-gold, sulphur-sulphur and oxygen-gold collisions at 200 GeV/nucleon has been studied in the NA35 Streamer Chamber experiment. Rapidity and transverse mass distributions as well as mean multiplicities were obtained. The results are compared with nucleon-nucleon data and with model predictions.

1 Introduction

It has been predicted that the phase transition from hadronic matter to quark-gluon plasma should result in an increased production of $s - \bar{s}$ pairs and thus of strange particles [1]. In previous papers we presented results on the production of neutral strange particles in proton-nucleus and nucleus-nucleus collisions at 200 GeV/nucleon [2, 3]. An increased yield of strangeness in central S+S collisions with respect to elementary p-p interactions was found [3]. In this paper we analyse the production of charged kaons in sulphur-sulphur, oxygen-gold, proton-sulphur and proton-gold collisions. Data on charged kaon production have already been published by the E802 Collaboration for Si+Au interactions at 14.6 GeV/nucleon [4] and by the Helios Collaboration for p+W and S+W interactions at 200 GeV/nucleon [5]. Both experiments have shown an increase of the K^+ / π^+ ratio around midrapidity as compared with the elementary interactions, while no such increase was observed for the K^- / π^- ratio. The data presented in this paper come from a significantly wider rapidity interval than those in the experiments mentioned above. It should be stressed that because K^+ and K^- are particle and antiparticle and because they belong to the different isospin multiplets they not only distinguish between s and $\bar{s}$ quarks but also provide information on the $q / \bar{q}$ ratio and thus on the baryochemical potential in the investigated reaction.

2 Experimental procedure

The data have been obtained in the NA35 Streamer Chamber experiment. The layout and the description of the apparatus were published elsewhere [6]. The following triggers were used:

- Minimum bias trigger, which selected about 90% of all collisions (p+S interactions).
- Forward energy trigger, which selected a fraction of all inelastic collisions, namely events with the energy deposited in the projectile fragmentation domain smaller than a given value (p+Au and A+A interactions).

The data samples consist of:

- 5590 p+S interactions, $\sigma \simeq 90\%$ of σ_{tot}
- 3535 p+Au interactions, $\sigma = 60\%$ of σ_{tot}
- 12825 S+S interactions, $\sigma = 2\%$ of σ_{tot}
- 3239 O+Au interactions, $\sigma = 6\%$ of σ_{tot}

at 200 GeV/nucleon. The thicknesses of the targets were 1165 mg/cm^2 and 940 mg/cm^2 for sulphur and gold respectively.

The streamer chamber pictures were scanned for 2-body-like decays with one charged secondary (kink topology) and for 3-body decays into charged secondaries

(tau topology). The secondary vertex and all the tracks of charged particles were required to be visible. These decays were measured, geometrically reconstructed and kinematically fitted assuming the $K^\pm$, $\Sigma^\pm$ and $\Xi^\pm$ hypotheses in order to identify them. The tau decays have a certain advantage over kinks because all particles, primary and secondaries, are detected as visible (and measurable) tracks which leads to four kinematic constraints in the fitting procedure. These decays practically do not suffer from the contamination by other particles. Unfortunately, the branching ratio for this decay mode is small (5.6%) such that tau decays give only a small fraction of our statistics. The main part of our data comes from kink-type decays. They have a large branching ratio (84.7% for 2-body decays), but they suffer from a contamination coming from decays of charged hyperons and from decays and elastic scatterings of pions. Because there is only one kinematic constraint, namely the mass of the primary particle, the results of a kinematic fit are often ambiguous. The method used for solving these problems will be discussed in detail.

For the analysis it was necessary to find a fiducial volume which should be essentially free of scanning and reconstruction losses. The life-time method used in the V^0 analysis for finding such a volume [2] was not applicable, because charged kaons have a very large life time ($c\tau_0 = 370 \text{ cm}$), such that in the streamer chamber only decays with life times less than $\sim 0.3 \tau$ were observed. This made it impossible to determine the apparent mean life time with a reasonable accuracy. Instead, we required the stability of the average multiplicity of kaons, taking into account only decays within certain geometrical limits in the streamer chamber space, as a function of these limits. It was found that the results are most sensitive to the width of the strip excluded in the central part of the streamer chamber, where the track density is very high (pencil cut). Fig. 1a shows the average multiplicity of K^+ and K^- in S+S interactions vs. the half width of this cut. It is seen that beginning from a width of the excluded strip of $\pm 20 \text{ cm}$ a stable value for $\langle K^+ \rangle$ and $\langle K^- \rangle$ is obtained. The pencil cut and the cut for lower corners of the streamer chamber were applied only to A+A collisions (the last one was introduced because the tracks in these regions were less visible and was different for S+S and O+Au interactions), while the cuts for the maximal rectangular dimensions of the fiducial volume, determined with the same method, were applied to all data. The same method was also used to find a lower cut for the projected decay angle. This cut was necessary because of scanning losses of kinks with a small decay angle. From Fig. 1b one can conclude that it is sufficient to apply a cut of 2° . The analysis was performed within the following y - p_t limits resulting from the geometrical restrictions and from the limited statistics: $0.6 < y < 2.4$ and $0.2 < y < 2.0$ for p+S, S+S and p+Au, O+Au respectively, with an upper p_t cut at $1.1 \text{ GeV}/c$. In Fig. 2 the detection probability of kaon decays in the y - p_t plane obtained with the cuts stated above is presented. The y - p_t regions in which the analysis was performed are marked. One should note that the acceptance for charged kaons covers the low p_t region, not accessible in V^0 studies. It was found that the contamination due to decays of charged hyperons in A+A interactions was negligible, as most of them decay within the excluded region. After applying a cut for the life time of $\tau/\tau_0 < 5$ it turned out that all particles fitted as kaons were true kaons, even if a fit gave a reasonable value for the probability (> 0.01) of a

hyperon hypothesis. This was not the case in p+S and p+Au collisions, for which a pencil cut was not applied. Using the VENUS Monte Carlo [7] it was found (see Fig. 3) that negative hyperons (Σ^- and Ξ^-) which decay in the streamer chamber and have an acceptable K^- fit (shadowed histogram) are a small fraction of true K^- for rapidity less than 2 and can thus be neglected. For rapidity greater than 2 all particles which gave a good hyperon fit were treated as true hyperons irrespectively of their K/Y ambiguities. The number of true K^- misidentified by this procedure is very small (see cross-hatched histogram in Fig. 3) and was not corrected for. The contamination of the K^+ sample by Σ^+ decays is significantly smaller than that of K^- by Σ^- and Ξ^- , because Σ^+ , having a very small (2.4 cm) $c\tau_0$ value, decay either outside the fiducial volume or, being very fast, give an unmeasurable (short and with a small curvature) track in the streamer chamber. In Table 1 the final numbers of K^+ and K^- used in the analysis are presented for all four reactions.

The VENUS model was also used to determine the contamination of the kaon sample by elastic scatterings and decays of pions. Pions were allowed to decay or scatter according to the corresponding decay or scattering laws and, after simulation of measurements, were run through a kinematic fit assuming the kaon hypotheses. The number of K -candidates from pions was calculated by normalisation to the measured pion multiplicity. The p_t and y distributions of K^+ and K^- were then obtained from the distributions of candidates (after applying the geometrical cuts) by applying the acceptance weights and subtracting the pion contamination. Fig. 4 shows the size of the corrections for this contamination in the rapidity and transverse mass distributions in S+S collisions. Results for p+S, p+Au and O+Au are similar.

3 Experimental results

3.1 Check of the consistency of the analysis

Since the sulphur nucleus has isospin zero, isospin symmetry implies that in S+S collisions the kaon production rates are related as

$$R_{K^+} + R_{K^-} = R_{K^0} + R_{\bar{K}^0} = 2 * R_{K_S^0}$$

Fig. 5 shows the normalized transverse mass $m_t = \sqrt{p_t^2 + m_K^2}$ distributions for the sum of K^+ and K^- and for $2 * K_S^0$, from Ref. [3], in the common rapidity domain $1.4 < y < 2.4$. The distributions agree both in slopes and absolute values, proving the consistency of the analysis and the validity of the obtained results.

3.2 Transverse mass and rapidity distributions

Figs. 6 and 7 show the normalized transverse mass and rapidity distributions for p+S, p+Au, S+S and O+Au interactions within the limited acceptance of the analysis. The spectra show an exponential behaviour with fitted slopes given in Table 2. The slope values in nucleus-nucleus collisions are seen to be very similar. Large statistical errors for p+S and p+Au interactions do not allow to draw any significant

conclusions for these reactions. The rapidity distributions for K^+ and K^- are similar in p+S and S+S collisions and in p+Au and O+Au collisions respectively, with a clear excess of K^+ over K^- . In p+Au and O+Au this excess appears in the lower rapidity domain as compared to p+S and S+S which suggests that a significant part of K^+ is produced in the fragmentation region of the heavy target nucleus, possibly in secondary processes.

3.3 Average multiplicities

Table 3 presents the average multiplicities of K^+ and K^- in the limited acceptance for all four reactions. An excess of K^+ over K^- is observed, which is stronger for the heavier target nucleus. In Table 4 the ratios of average multiplicities in S+S to p+S and O+Au to p+Au collisions within the limited y - p_t range are given. There is no significant difference of these ratios for K^+ and K^- . In Fig. 8 the ratios of the sum ($\langle K^+ \rangle + \langle K^- \rangle$) in the limited acceptance to the average multiplicity of negative hadrons $\langle n_- \rangle$ in 4π are plotted for the given values of $\langle n_- \rangle$ in nucleon-nucleon, proton-nucleus and nucleus-nucleus reactions. The proton-nucleus and the nucleus-nucleus data on $\langle n_- \rangle$ come from Ref. [8]. The nucleon-nucleon data were obtained from Ref. [9]. One sees an increase of this ratio from nucleon-nucleon to proton-nucleus interactions. There is no further increase from p+S to S+S, and one sees a decrease from p+Au to O+Au collisions, however it should be stressed that the acceptance regions for p+A and A+A are not fully comparable because of the backward shift of the rapidity distributions in proton-nucleus with respect to nucleus-nucleus interactions. As the acceptance in rapidity is limited to the backward hemisphere, it means that for p+A relatively more strange particles are observed than in more symmetric central collisions of nuclei. This effect should increase with increasing asymmetry of the colliding system.

4 Comparison with models

In Figs. 9-12 the transverse mass and rapidity distributions for the four reactions are compared with the predictions of the VENUS [7] and FRITIOF [10] models. The Monte Carlo events for nucleus-nucleus collisions were generated with an upper cut on impact parameter to match the fraction of the total cross section given by the experiment (see section 2). For proton-nucleus reactions they were generated without such restrictions.

The slopes of the m_t distributions predicted by both models are included in Table 2. The transverse mass distributions for K^+ are relatively well described by VENUS, except perhaps for p+S collisions. This sample, however has low statistics (see Table 1) and it is hard to draw a firm conclusion. Negative kaons show a flatter m_t distribution than the models, except for p+Au, for which the previous remark is valid as well.

Both models describe the K^- rapidity distributions better than the ones for K^+ . In Tables 3 and 4 the results on average multiplicities are compared with the model predictions. One sees from Table 3 that the p+S data are rather well described

by both models. For the other reactions FRITIOF seems to underpredict the K^+ yield, while VENUS describes it better. Both models seem to overpredict the average K^- multiplicity in nucleus-nucleus collisions. The ratios of the average K^+ and K^- multiplicities in S+S to p+S collisions is rather well predicted by both models, while they overpredict the corresponding ratios for O+Au to p+Au reactions (Table 4) This is probably due to the fact that our p+Au sample is not really a minimum bias sample, but corresponds to 60% of σ_{tot} .

5 Extrapolation of the S+S results to the full phase space

The symmetry of the colliding system in S+S interactions allows to extrapolate the multiplicity results to the full phase space. For this we assume that the slopes of the m_t distributions obtained in the limited rapidity interval are valid in the whole rapidity range, and that the rapidity distributions have a Gaussian shape. The extrapolated results are presented in Table 5 and compared with the models and with nucleon-nucleon data [9]. The quoted errors are statistical only. The systematic errors of the extrapolation were estimated to be $\sim 3\%$.

The K^-/π^- ratio is not enhanced significantly as compared to nucleon-nucleon collisions, while the K^+/π^+ ratio shows an increase by a factor of about 1.5. Both models underestimate the K^+/π^+ ratio, but reproduce quite well the K^-/π^- ratio.

Using already published data on Λ and $\bar{\Lambda}$ production [3] we have calculated the excess of hyperons (Y) over antihyperons ($\bar{Y}$) in full phase space and compared it with the result obtained from K^+ and K^- :

$$\langle K \rangle_{net} = 2 * (\langle K^+ \rangle - \langle K^- \rangle) = 11.2 \pm 1.3$$

$$\langle Y \rangle_{net} = 1.6 * (\langle \Lambda + \Sigma^0 \rangle - \langle \bar{\Lambda} + \bar{\Sigma}^0 \rangle) = 10.7 \pm 1.6$$

The factor 2 accounts for K^0 and $\bar{K}^0$, the scaling factor 1.6 is taken from Ref. [11] and accounts for the unobserved hyperons. The excess of hyperons over antihyperons is seen to be matched by an excess of K^+ (and K^0) as expected from strangeness conservation. This excess amounts to 70% of the sum of hyperons and antihyperons, whereas it is only 27% of all kaons. Taking into account the small rate of $\bar{Y}$ and the absence of enhancement of the K^- / π^- ratio it can be concluded that a larger part of the observed increased strangeness production appears as $K - Y$ pairs. Such a result is qualitatively expected both for the hadronisation of a phase with high net baryon density [1, 12] and in purely hadronic models of rescattering of produced particles in a baryon rich environment [1, 13].

6 Summary and conclusions

We have studied the production of K^+ and K^- in p+S, p+Au, S+S and O+Au collisions at 200 GeV/nucleon. Within the acceptance of the experiment the following main results have been obtained:

1. The transverse mass distributions show an exponential behaviour with similar values of the slopes for the different reactions. With the available statistical accuracy no significant difference between the slopes for K^+ and K^- is observed.
2. An excess of K^+ over K^- is observed, which is shifted backwards in rapidity for p+Au and O+Au with respect to p+S and S+S collisions.
3. The ratio of the sum $\langle K^+ \rangle + \langle K^- \rangle$ in the limited acceptance to the average multiplicity of negative hadrons in the full phase space increases by a factor of about 1.5 from nucleon-nucleon to proton-nucleus interactions, while no further increase is observed when going from proton-nucleus to nucleus-nucleus collisions. This result, however, is biased by the limited acceptance of the experiment.
4. Neither the FRITIOF nor the VENUS model gives a satisfactory description of the full set of the results; however they succeed to predict some features. The VENUS model seems to describe the data better than FRITIOF.
5. S+S data extrapolated to the full phase space show that the observed strangeness enhancement appears mainly as *kaon - hyperon* pairs which indicates that this enhancement comes from the region of nonzero baryochemical potential.

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Table 1

Statistics of the bias free samples of charged kaons

Reaction	Rapidity range	Number of K^+	Number of K^-
$p + S$	0.6 - 2.4	60	42
$p + Au$	0.2 - 2.0	127	64
$S + S$	0.6 - 2.4	636	315
$O + Au$	0.2 - 2.0	298	134

Table 2

Fits of the form $\frac{1}{m_t} \frac{dN}{dm_t} = C e^{-Am_t}$ to the transverse mass distributions.

Reaction	Rapidity range	Data		Venus		Fritiof	
		A_{K+}	A_{K-}	A_{K+}	A_{K-}	A_{K+}	A_{K-}
p + S	0.6 - 2.4	$4.4 \pm_{1.1}^{0.9}$	$3.5 \pm_{1.4}^{1.1}$	6.2 ± 0.2	7.3 ± 0.3	6.8 ± 0.2	6.1 ± 0.2
p + Au	0.2 - 2.0	$7.1 \pm_{1.1}^{0.9}$	$8.1 \pm_{2.3}^{1.6}$	6.3 ± 0.2	6.3 ± 0.3	7.0 ± 0.2	5.9 ± 0.2
S + S	0.6 - 2.4	4.4 ± 0.3	3.7 ± 0.5	5.24 ± 0.06	5.49 ± 0.07	6.78 ± 0.08	6.21 ± 0.09
O + Au	0.2 - 2.0	4.7 ± 0.4	4.0 ± 0.7	5.11 ± 0.06	5.29 ± 0.09	6.89 ± 0.09	6.23 ± 0.09

Table 3

Average multiplicities of K^+ and K^- in the limited phase space regions.

Reaction	Rapidity range	Data		Venus		Fritiof	
		$\langle K^+ \rangle$	$\langle K^- \rangle$	$\langle K^+ \rangle$	$\langle K^- \rangle$	$\langle K^+ \rangle$	$\langle K^- \rangle$
p + S	0.6 - 2.4	0.15 ± 0.02	0.10 ± 0.02	0.18	0.12	0.17	0.11
p + Au	0.2 - 2.0	0.32 ± 0.03	0.16 ± 0.03	0.26	0.14	0.19	0.13
S + S	0.6 - 2.4	3.31 ± 0.17	1.69 ± 0.19	2.98	2.03	2.67	1.89
O + Au	0.2 - 2.0	3.9 ± 0.3	1.7 ± 0.2	3.71	2.11	3.58	2.43

Table 4

Ratios of average multiplicities of K^+ and K^- in nucleus-nucleus to proton-nucleus collisions.

	Rapidity range	Data		Venus		Fritiof	
		K^+	K^-	K^+	K^-	K^+	K^-
$S + S / p + S$	0.6 - 2.4	22 ± 3	17 ± 4	17	17	16	17
$O + Au / p + Au$	0.2 - 2.0	12 ± 2	11 ± 2	14	15	19	19

Table 5

Average multiplicities of K^+ and K^- and multiplicity ratios in $S + S$ interactions extrapolated to the full phase space. Included are $N + N$ results for comparison.

	$\langle K^+ \rangle$	$\langle K^- \rangle$	$\frac{\langle K^+ \rangle}{\langle \pi^+ \rangle}$	$\frac{\langle K^- \rangle}{\langle \pi^- \rangle}$	$\frac{\langle K^+ \rangle}{\langle K^- \rangle}$
Data	12.5 ± 0.4	6.9 ± 0.4	0.137 ± 0.008	0.076 ± 0.005	1.81 ± 0.12
Venus	10.57	7.48	0.117	0.083	1.41
Fritiof	9.35	7.02	0.102	0.077	1.33
$N + N$	0.24 ± 0.06	0.17 ± 0.05	0.08 ± 0.01	0.06 ± 0.01	1.42 ± 0.5

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Figure captions

Fig. 1

Average multiplicities of charged kaons in S + S collisions vs. the beam pencil cut (a) and the lower cut of the decay angle projected onto the film plane (b).

Fig. 2

Probability of the detection of kaon decays within the fiducial volume of the streamer chamber for p + S (a), p + Au (b), S + S (c) and O + Au (d) interactions at 200 GeV/nucleon. The acceptance regions within which the analysis was performed are marked.

Fig. 3

Rapidity and transverse momentum distributions for negative strange particles decaying within the fiducial volume of the streamer chamber in p + Au interactions at 200 GeV/c (VENUS model). The solid histogram corresponds to all such particles fitted as K^- , the shaded histogram corresponds to hyperons (Σ^- and Ξ^-) fitted as K^- and the cross-hatched histogram corresponds to true K^- fitted as negative hyperons.

Fig.4

Rapidity and transverse mass distributions for charged kaons in S + S interactions at 200 GeV/nucleon. Squares represent the raw data, while triangles show the distributions corrected for the pion contamination.

Fig. 5

Transverse mass distributions for the sum $K^+ + K^-$ (triangles) and for $2 * K_S^0$ (circles) in S + S collisions within the common rapidity range $1.4 < y < 2.4$.

Fig. 6

Transverse mass and rapidity distributions for charged kaons in p + S (a and b) and p + Au (c and d) interactions. The full lines show results of an exponential fit. The values of the slopes are given in Table 2.

Fig. 7

Transverse mass and rapidity distributions for charged kaons in S + S (a and b) and O + Au (c and d) interactions. The full lines show results of an exponential fit. The values of the slopes are given in Table 2.

Fig. 8

Ratio of the sum ($\langle K^+ \rangle + \langle K^- \rangle$) in the limited acceptance to the total average multiplicity of negative hadrons in N + N, p + S and S + S (a) and in N + N, p + Au and O + Au (b) interactions plotted for the given values of $\langle n_- \rangle$ in these reactions. Note that the acceptances in rapidity for (a) and (b) are different .

Fig. 9

Transverse mass and rapidity distributions for positive (a and c) and negative (b and d) kaons in p + S interactions within the limited acceptance, compared with

the predictions of the VENUS (dashed line) and FRITIOF (dotted line) models.

Fig. 10

Transverse mass and rapidity distributions for positive (a and c) and negative (b and d) kaons in p + Au interactions within the limited acceptance, compared with the predictions of the VENUS (dashed line) and FRITIOF (dotted line) models.

Fig. 11

Transverse mass and rapidity distributions for positive (a and c) and negative (b and d) kaons in S + S interactions within the limited acceptance, compared with the predictions of the VENUS (dashed line) and FRITIOF (dotted line) models.

Fig. 12

Transverse mass and rapidity distributions for positive (a and c) and negative (b and d) kaons in O + Au interactions within the limited acceptance, compared with the predictions of the VENUS (dashed line) and FRITIOF (dotted line) models.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12