KAON PRODUCTION IN HIGH ENERGY NUCLEUS–NUCLEUS COLLISIONS

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The K^+ production cross section is calculated for the Ne + NaF system at 2.1 GeV/*A* in the frame of a three-dimensio cascade model. Good agreement with experimental data is obtained when the kaons are assumed to rescatter once before escaping the system.

The detection of strange particles like K^+ is expected to help us to get more information about the hot compressed matter created during the high energy nucleus–nucleus collisions. Although only one experiment [1] has been performed so far, the situation seemed very promising. Due to the proximity of the strangeness production threshold, the K^+ particles are expected to be produced in the early stage of the collision process, when the nucleon–nucleon collisions are still very energetic. Furthermore, as emphasized by Nagamiya [2], the K^+ having a long mean free path, compared to pions and nucleons, they are able to escape easily and the properties of the observed K^+'s should reflect the properties of the hot phase at its formation. It is indeed striking that the exponential slope parameter, in some sense the "temperature", is for the same system, decreasing when going from the kaons to nucleons and to pions, i.e. towards decreasing mean free path, or towards later emission times (assuming the two quantities are related in a simple manner).

However, the situation is not as simple as it seems. It is known that observed proton and (to a lesser extent) pion spectra are not isotropic, indicating that the system has not been completely thermalized. Detailed analyses of the 90° CM spectra in symmetric systems show that even though they are fairly exponentially decreasing, they are very likely built from different contributions, coming from nucleons having made 1, 2, ..., n collisions. Each contribution has a different slope, not necessarily exponential. Only the sum of this contribution appears exponential [3,4]. Moreover, the lower the number n of collisions the less isotropic tl cross section is. To summarize, it seems that only a fraction of the system is thermalized, and this happe rather late in the collision process. That is what mul ple scattering models able to reproduce the data ten to indicate. Therefore, the K^+ data are somewhat pu zling and it is hard to accept that a thermalized phas is created in the early stage of the evolution process. Before drawing any conclusion, it is important to kr whether the K^+ production features are or are not e plainable by multiple scattering models.

The first attempt in this direction was done by Randrup and Ko [5]. They calculated the K^+ cross s tion in the linear cascade model [6], assuming the ka are produced in baryon–baryon collisions. They ess tially found too few kaons (see however later on) wi a too much forward peaked angular distribution, eve when rescattering of kaons is managed [7]. We want here to take the problem again, but in using the mor realistic three-dimensional cascade code of ref. [8]. I sentially, the same physics is involved. However, the lack of communication between the "tubes" in the l ear cascade model drastically limits the number of b ry nucleon–nucleon collisions in comparison to a th dimensional cascade model. In a 3D-cascade, the "clusters" are noticeably larger than in the linear cas cade [9], indicating the presence of a non-negligible communication between "tubes". The energetic nucleon–nucleon collisions, capable of producing a K^+

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particle, are believed to occur inside a tube only. Our calculation can be viewed as a check of this hypothesis, and a check of the approach of ref. [5] in general.

The cascade code that we have used is described in detail in ref. [8]. It is sufficient to say here that in such an approach the collision process is viewed as a succession of time ordered binary baryon–baryon collisions proceeding as in free space. The explicit treatment of the kaons in such an approach demands a deep modification of the numerical code and a strong numerical effort. Owing to the small elementary K^+ production cross section, we have used a perturbation approach. We run the cascade code without explicit reference to the kaons, and we record the whole sequence of binary collisions. For any event, we thus know the nature B and B′ of the partners of the successive binary collisions, as well as their four-momenta p_B and $p_{B'}$. We evaluate the invariant K^+ production as

$$E_K\,d^3\sigma/dp_K^3 = 2\pi \sum_i \frac{(\Delta b) b_i}{N_{ev}} \sum_{ev} \sum_{\substack{coll \\ s>s_0}} \frac{1}{\sigma^{tot}_{BB'}} E_K \times d^3\sigma(p_B + p_{B'} \to p_K)\,dp_K^3, \quad (1)$$

where the first sum runs over the impact parameters, the second sum over the events and the third sum over the binary collisions for which the (squared) CM energy s is larger than the threshold value s_0 of the process $B + B' \to K^+ + X + X'$ (to be precised later). The quantity $\sigma^{tot}_{BB'}$ is the total BB′ cross section at CM energy $\sqrt{s}$ and the last quantity is the experimental cross section for production of a kaon with momentum p_K from a collision of baryons B and B′ with momenta p_B and $p_{B'}$ respectively. The latter are the values calculated in the cascade process. Finally N_{ev} is the number of events per impact parameter. Eq. (1) is a discretization of a more general formula

$$E_K \frac{d^3\sigma}{dp_K^3} = \int 2\pi b\,db \int \frac{d^3p_B}{E_B}\frac{d^3p_{B'}}{E_{B'}} f(p_B, p_{B'}) \times [\sigma^{tot}_{BB'}(s)]^{-1} E_K\,d^3\sigma(p_B + p_{B'} \to p_K)/dp_K^3, \quad (2)$$

where $f(p_B, p_{B'})$ is the probability of having a collision between a baryon B and a baryon B′ with four-momenta p_B and $p_{B'}$, respectively. The perturbation approach is justified by the small ratio between the total elementary K^+ cross section to the total baryon–baryon cross section ($\sim 10^{-3}$, see fig. 1). The calcula ed function f is surprisingly high. About 35% of the binary collisions are above the NΛK threshold for ($b = 0$) central collisions.

We have considered, as in ref. [5], the following production reactions:

$$\{NN, N\Delta \text{ or } \Delta\Delta\} \to \{N\Lambda K, N\Sigma K, \Delta\Lambda K \text{ or } \Delta\Sigma K\}. \quad (3$$

The cross sections have been parametrized as

$$E_K\,d^3\sigma/dp_K^3 = \sigma_0 (p_{max}/m_K c)(E_K/4\pi p_K^2) \times (12/p_{max})(1 - p_K/p_{max})(p_K/p_{max})^2 \quad (4$$

where p_{max} is the maximum kaon momentum for th available CM energy $\sqrt{s}$. The quantity σ_0 (equal to the integrated cross section for $p_{max} = m_K c$, $\sigma_{int} = \sigma_0\,p_{max}/m_K$) has been extracted from experiment as shown in fig. 1, for three different final channels o the pp system. The same data have been used by the authors or ref. [5], but their values of σ_0 are errone-

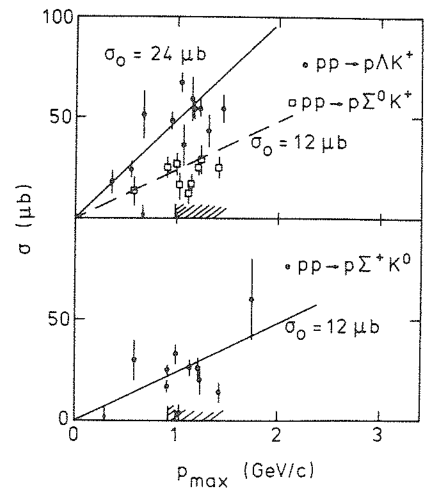

Fig. 1. Measurements of different K^+ producing reactions (from ref. [19]) compared with the representation of eq. (1) (see text). The associated values of σ_0 are indicated. The quantity p_{max} is the maximum K^+ momentum and is a uniq function of the CM energy. The arrows indicate (for the pΛK channel in the upper part and for the pΣK channel in the lower part) the value of p_{max} corresponding to a NN system with a 2.1 GeV incident lab kinetic energy. The shaded area gives the boundary of the domain of p_{max} attainable in the symmetric nucleus–nucleus system owing to the Fermi motion. The same kinematics is considered.

ously too small by a factor 2 [‡1]. The rest of input data (isospin average, angular distribution) are kept the same as in ref. [5].

The results are shown in figs. 2–4. In figs. 2 and 3 we have presented the proton and pion cross sections in order to show the general good predictability of the model, similar to the one achieved around 800 MeV/A [11]. This gives a rather good confidence to the ability of the model to provide a reliable general dynamical scheme.

Fig. 4 contains the main result of this work. It shows the predictions of eq. (1) (summed of all processes (3)), in dotted curves, in comparison with the measurements of ref. [1]. As for the calculation of ref. [5], we have too large a cross section at 15° (more or less the mid-rapidity region) and too small a cross section at large angles. When the results of ref. [5] are scaled to use our values of the parameter σ_0, our calculation presents only a slight improvement. They are also very close to the results of a diffusion model calculation of a paper by Schürmann et al. [12]. As a conclusion, it seems that the transverse communication between the "tubes", neglected in the linear cascade is not mediated by very energetic collisions. This is probably due to the very forward peaked NN cross section in this energy range.

The full curves in fig. 4 are obtained by applying a correction to eq. (1) to take care of the possible rescattering of the kaons by the baryons. We assume that the kaons are rescattered once. This seems reasonable, in view of the nuclear dimension and the K^+N cross sec-

‡1 After submitting the first version of the manuscript, we have been told that this error has since been found and corrected by Randrup and Ko [10].

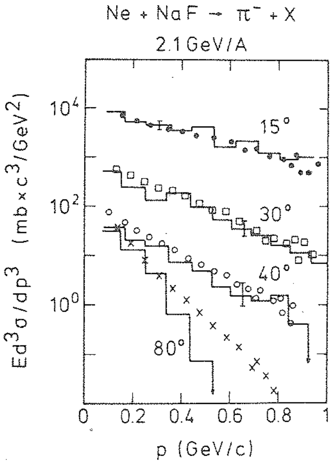

Fig. 3. Same as fig. 2 for the negative pions.

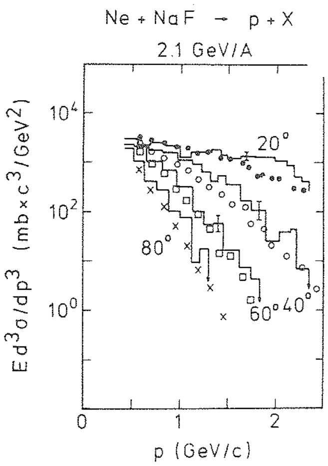

Fig. 2. Comparison of the inclusive proton cross section (taken from the measurements of ref. [20]) with the predictions of our calculation. The error bars give the typical uncertainty of the calculation.

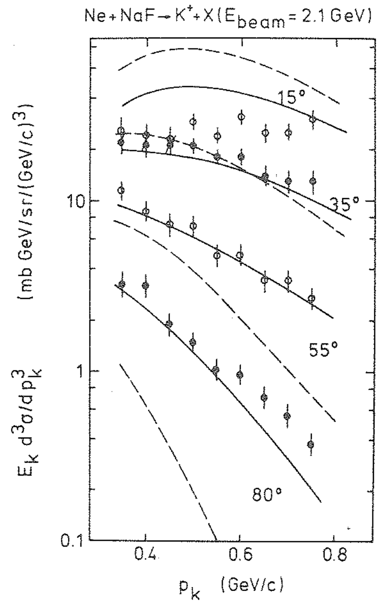

Fig. 4. K^+ cross sections. Measurements are from ref. [1]. The dotted lines give the primordial K^+ cross section as calculated in the intranuclear cascade model. The full curves are obtained by applying the correction factor (eq. (6), see text).

tion. With known values, and for a compression ratio of 2, the mean free path equals the nuclear radius of the system under consideration. This rescattering is a little bit more frequent than the one considered in ref. [7], which, for the same system, considered that the average number of rescatterings is $\kappa = 0.68$. The difference comes from the higher density considered here, in keeping with the results of the cascade calculation itself. The correction has been estimated using a diffusion model, similar to ref. [13]. Let $f_0(p)$ and $f_1(p)$ be the primordial and final kaon momentum distributions (having made one collision with a nucleon). Assuming that the nucleons are acting as a thermal bath with temperature τ, the quantities f_0 and f_1 are related by

$$f_1(p) = (\pi d)^{-3/2} \times \int d^3p' \exp\{-[p-(1-\beta)p']^2/d\} f_0(p'). \quad (5)$$

In this relation, β is the average fraction of the kaon momentum lost during the collision. Considerations on the kinematics show that $\beta \approx m_K/(m+m_K) \approx 0.3$, if the cross section can be considered as isotropic. The quantity d is equal to $4m\tau\beta^2$ [13]. If one further assumes that $f_0(p')$ has a boltzmannian shape with a temperature T, the correction can be put in a closed form

$$C(p) = f_1(p)/f_0(p) = \{2m_K T/[(1-\beta)^2\, 2m_K T + 4m\tau\beta^2]\}^{3/2} \times \exp\{-(p^2/2m_K T) \times \{1-[(1-\beta)^2 + 4m\tau\beta^2/2m_K T]^{-1}\}\}. \quad (6)$$

In fig. 4, we have applied this correction factor to our calculated primordial K^+ spectrum, choosing $\tau = 120$ MeV, around the observed proton slope parameter and $T = 80$ MeV. The latter choice is consistent with the fall-off of the calculated primordial K^+ spectrum. We note that the correction leads to a dramatic narrowing of spectra in fig. 4, bringing the results close to experimental data. We do not pretend that we have an accurate description of the rescattering. We just wanted to show that the experimental data can be obtained from the calculated primordial K^+ cross section by a reasonable (simplified, of course) picture of the rescattering.

The respective contribution of the various strangeness producing channels to the integrated production cross section are contained in table 1. The total calculated cross section (strictly independent of the details of the kaon rescattering) agrees quite well with the estimated experimental cross section [21], $\sigma_{exp} = 23 \pm 8$ mb. This is an important point, since the strangeness number density could be a signal of exotic phases, according to ref. [14].

Table 1
Contribution of the different channels to the production cross section

Channel	σ [mb]
$N\Lambda K$	9.26
$N\Sigma K$	6.94
$\Delta\Lambda K$	2.18
$\Delta\Sigma K$	1.28
sum	19.66

In conclusion, we have presented a calculation of the K^+ production at 2.1 GeV per nucleon based on a cascade dynamical picture. The results are in good agreement with experiment when a reasonable estimate of the kaon rescattering by the nucleons is introduced. The large slope parameter for the kaons thus seems to have a slightly different origin from the proton case. For the latter, multiple scattering is important. For the former, only one scattering is sufficient to broaden very much the momentum distribution in the CM system, which at the beginning is fairly narrow, in a gas dynamical picture. The reason comes from the rather small energy delivered to the kaon in a NN collision in this energy range. As nicely shown in ref. [5], the momentum distribution would be even much narrower without the influence of the Fermi motion.

We would like to point out that our results as well as the one obtained by Schürmann et al. [12] are much better than any other existing calculation (note, however, the uncertainty in the input of the calculation, fig. 1), especially those obtained in equilibrium models [15], or in phase space model [16]. We have however to note that Biro et al. [17] arrived at good results in a model with thermal equilibrium but without chemical equilibrium. The fact that the kaons are not in chemical equilibrium with the other species despite the high temperature is in keeping with the small elementary production cross section, a feature which is crucial in our treatment. They however conclude that the

$\pi N \to \Lambda K$ reaction is an important source of strangeness production (see also ref. [18]). If it is true that the associated cross section is important, the pions, however, appear rather late in the collision process and it is doubtful that they will provide sufficiently enough energetic πN pairs. This should be treated in a more realistic calculation.

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