ELSEVIER

6 February 1997

PHYSICS LETTERS B

Physics Letters B 393 (1997) 31-35

Pion and kaon emission from the fireball formed in Ne + NaF collisions at 1–2 GeV/nucleon

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Received 30 August 1996; revised manuscript received 25 October 1996
Editor: R.H. Siemssen

Abstract

Double differential cross sections for proton, π^+ and K^+ meson production have been measured in Ne + NaF collisions at 1 and 2 GeV/nucleon. Parameterizations of the meson spectra with Maxwell–Boltzmann distributions yield common inverse slope parameters for kaons and high-energy pions at each beam energy. No evidence for different freeze out temperatures can be deduced from the spectral slopes of the emitted particles.

PACS: 25.75.+r

The production of mesons probes the reaction dynamics and the properties of the matter in the reaction zone of two colliding nuclei [1]. In the initial stage of a heavy ion collision at energies between 1 and 2 GeV/nucleon, the matter in the overlap region is compressed to 2–3 times saturation density ρ_o [2]. At these densities, thermalization may be reached rapidly via binary encounters of the nucleons. Inelastic nucleon–nucleon collisions lead to the production of baryonic resonances and mesons. In the subsequent expansion phase, the matter in the reaction volume cools down and the different particle species "freeze out" at time scales according to their respective mean free path. The produced pions interact strongly with the surrounding matter up to the late stages of the expansion. In contrast to the pions, the K^+ mesons decouple early and are thus messengers of the hot and dense reaction zone, as their mean free path is long due to the absence of K^+N resonances.

Different assumptions about the reaction dynamics

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PII S0370-2693(96)01568-7

and the freeze-out process lead to different predictions for the spectral shapes of the final state particles:

(i) A simple thermal model is suggested by the observation that most of the measured particle spectra can be roughly described by Maxwell–Boltzmann distributions $d^3\sigma/dp^3 \propto \exp(-E/T)$. In such a model the inverse slope parameter T corresponds to the temperature of the particle emitting source. It has been argued that different freeze-out times manifest themselves in different slopes of the energy spectra for pions, kaons and protons [3]. The K^+ mesons still carry information of the hot phase of the collision, whereas the pions have large inelastic cross sections and therefore decouple from the participating nucleons in a late and colder phase ($T_{K^+} > T_p \approx T_\pi$). This interpretation was supported by the apparent observation that the K^+ inverse slope parameter seemed to be larger than the ones of the protons and pions in Ne + NaF collisions at 2.1 GeV/nucleon [4].

(ii) The spectra of produced particles should be affected by the phase space of the individual NN collisions. At bombarding energies below or close to their free NN threshold of 1.58 GeV, the K^+ mesons have necessarily low c.m. energies, in contrast to the pions. This results in a smaller inverse slope parameter for kaons than for protons and pions ($T_p \approx T_\pi > T_{K^+}$).

(iii) It has been found experimentally that the spectral distributions of the emitted baryons and light fragments are strongly influenced by their collective radial motion which is due to the expansion of the compressed reaction zone [5,6]. This effect increases the inverse slope parameter with increasing particle mass ($T_p > T_{K^+} > T_\pi$).

(iv) There is strong evidence that pion production at intermediate energies proceeds via the excitation and subsequent decay of intermediate baryonic resonances, mainly Δ_{1232} [7]. In this scenario, the decay kinematics $\Delta \to N\pi$ dominates the pion spectral slopes [8–10].

In order to study the influence of the above mechanisms to the observed particle spectra we have measured the energy distributions of pions and kaons produced in collisions between nuclei of different size at different bombarding energies [9,11]. For light collision systems K^+ production was studied so far only for bombarding energies above the free NN threshold [12,13]. Here we present first experimental data on subthreshold K^+ production in collisions between light nuclei. We have measured K^+ and π^+ double differential cross sections in Ne + NaF collisions at 1 GeV/nucleon and, for comparison, the same system at 2 GeV/nucleon.

Table 1
Angular ranges in the c.m. system as covered by the experiment.

	1 GeV/nucl.	2 GeV/nucl.
protons	$90° < \Theta_{cm} < 155°$	$115° < \Theta_{cm} < 155°$
pions	$73° < \Theta_{cm} < 85°$	$85° < \Theta_{cm} < 97°$
kaons	$77° < \Theta_{cm} < 120°$	$95° < \Theta_{cm} < 130°$

The experiments have been performed with the magnetic spectrometer KaoS installed at the heavy ion synchrotron SIS and GSI Darmstadt [14]. KaoS has a large acceptance in solid angle ($\Omega \approx 30$ msr) and a momentum range ($p_{max}/p_{min} \approx 2$ up to 1.8 GeV/c). Meson decay in flight is minimized by short trajectories of 5–6.5 m. The large proton to kaon ratio ($10^4 : 1$) requires an efficient kaon trigger which is based on a simultaneous time-of-flight and momentum measurement and, for high momentum kaons, on a threshold Cherenkov detector. Trajectory reconstruction for background suppression and kaon identification is based on two large area multi-wire chambers.

The ^{20}Ne-beam had an intensity of 10^7 ions per spill and impinged on a NaF target of 0.45 g/cm^2 thickness. The particles were measured within a polar angular range of $40° < \Theta_{lab} < 48°$ and within a momentum range of 0.3 GeV/c $< p_{lab} <$ 1.15 GeV/c. The resulting coverage for the c.m. angles is given in Table 1.

The beam intensity was monitored by the pion rate measured in the spectrometer. The ratio of pions to beam particles was calibrated by a measurement at reduced beam intensity. At this reduced rate, the beam particles could be counted individually with a movable thin plastic scintillator located 30 cm upstream of the target. This procedure was used for the kaon and pion data measured in Ne + NaF collisions at 1 GeV/nucleon (Fig. 1). At 2 GeV/nucleon, the absolute normalization of the data is based on the total inclusive pion production cross section. Taking the energy dependence of pion production from Ar + KCl data measured in the energy range from 0.4 to 1.8 GeV/nucleon [15], we scale the pion cross section

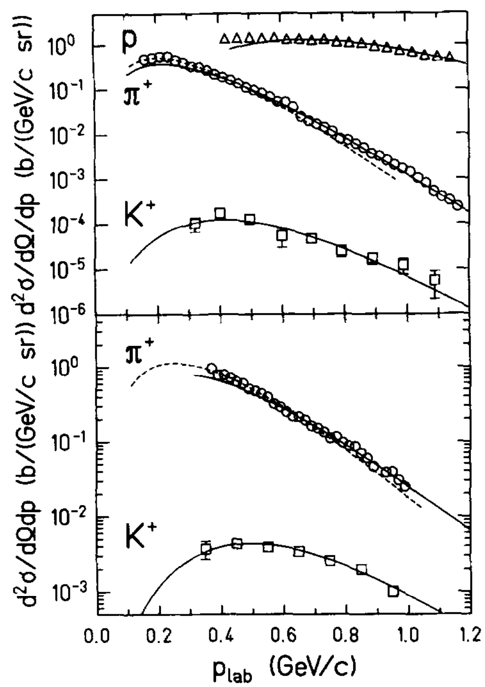

Fig. 1. Inclusive double-differential cross sections for particle production in Ne+NaF collisions as a function of laboratory momentum. Upper part: protons, π^+ and K^+ measured at 1 GeV/nucleon beam energy. Lower part: π^+ and K^+ measured at 2 GeV/nucleon. The data are taken at $40^\circ < \Theta_{lab} < 48^\circ$. The lines represent Maxwell–Boltzmann distributions fitted to the data (see text). The resulting inverse slope parameters are given in Table 2.

measured in Ne + NaF at 1 GeV/nucleon (as shown in Fig. 1 upper part) to 2 GeV/nucleon by the factor 2.75. The uncertainty of this method arises from the possible change of the pion angular distribution with beam energy. The angular anisotropy of pions from Ar + KCl at 0.8 and 1.8 GeV/nucleon was found to be similar [8,16]. We attribute an overall systematic error of 40% to the total cross sections measured at 2 GeV/nucleon. The shape of the kaon and pion spectra and their ratio are not affected by this procedure.

The double differential cross sections $d^2\sigma(dpd\Omega)$ for protons, π^+ and K^+ measured at 1 GeV/nucleon and 2 GeV/nucleon beam energy are shown in the upper and lower part of Fig. 1, respectively. The error bars are due to statistics only. For the data taken at 1 GeV/nucleon, there is a systematic error of 22% which accounts for uncertainties from beam normalisation (12%), spectrometer acceptance (5%) and efficiencies of the trigger (10%) and of the tracking method (15%). At 2 GeV/nucleon, the total systematic error is 40%.

The pions, kaons and also the high energy protons are measured around $\Theta_{cm} \approx 90^\circ$ (see Table 1) where final state interaction of the mesons with spectator matter should be reduced. Therefore, in a first step, one can try to extract thermal properties of the reaction zone from these particle spectra. The data are compared to Maxwell–Boltzmann distributions $d^2\sigma/(p^2dpd\Omega) \propto \exp(-E/T)$ which are fitted to the experimental data after transformation into the NN c.m. frame. The resulting inverse slope parameters are listed in Table 2 together with the values measured for Au + Au collisions at 1 GeV/nucleon [11]. The pion spectra cannot be described properly with a single inverse slope parameter. This is demonstrated by the fits to the pion spectra which take into account either the low pion energies only ($E_{cm}^{kin} < 0.25$ GeV, dashed lines in Fig. 1) or the pions above this energy (solid lines in Fig. 1 and Fig. 2). The low energy part of the proton spectrum is dominated by target spectators and hence not included in the fit (Fig. 1). The proton inverse slope parameters for Ne + NaF and Au + Au at 1 GeV/nucleon as given in Table 2 are larger than the corresponding meson values by about 20 MeV and 30 MeV, respectively. It has been found, that large inverse slope parameters for protons as compared to pions are a signature of radial flow [17].

Fig. 2 shows double-differential cross sections $d^2\sigma/(p^2dpd\Omega)$ for π^+ and K^+ measured in Ne+NaF collisions as a function of the c.m. kinetic energy. In this representation Maxwell–Boltzmann distributions appear as straight lines. The fits to the high energy parts of the pion spectra ($E_{cm}^{kin} > 0.25$ GeV) and to the K^+ spectra result – within the errors – in identical inverse slope parameters for each beam energy (see Table 2). The deviation of the low energy part of the pion spectra from simple Maxwell–Boltzmann distributions as indicated in Fig. 2 was also found in earlier studies [8,9] and was related to the decay of the delta resonance $\Delta \to \pi N$.

Baryonic resonances are expected to play a key role also in subthreshold kaon production [18]. Multiple collisions with a Δ resonance excited in a first step followed by the reaction $\Delta N \to YK^+N$ ($Y = \Sigma, \Lambda$) are regarded as the dominant K^+ production channel in nucleus–nucleus collisions below the free NN threshold [19,20]. In this sequential process the resonance

Table 2
Inverse slope parameters in MeV for π^+, K^+ and protons and K^+/π^+ ratios measured around Θ_{cm} = 90°. $T^{low}_{\pi^+}$ and $T^{high}_{\pi^+}$ corresponds to pion energies below and above E^{kin}_{cm} = 250 MeV, respectively. T_p (MeV) is for protons with p_{lab} < 700 MeV/c (see text).

system	$T^{low}_{\pi^+}$	$T^{high}_{\pi^+}$	T_{K^+}	T_p	K^+/π^+
Ne + NaF 1 GeV/n	54 ± 3	60 ± 3	61 ± 6	76 ± 4	$3.9 \pm 0.8 \times 10^{-4}$
Ne + NaF 2 GeV/n	71 ± 3	79 ± 3	79 ± 6		$7.4 \pm 1.0 \times 10^{-3}$
Au + Au 1 GeV/n	60 ± 3	74 ± 3	67 ± 6	98 ± 7	$3.0 \pm 1.0 \times 10^{-3}$

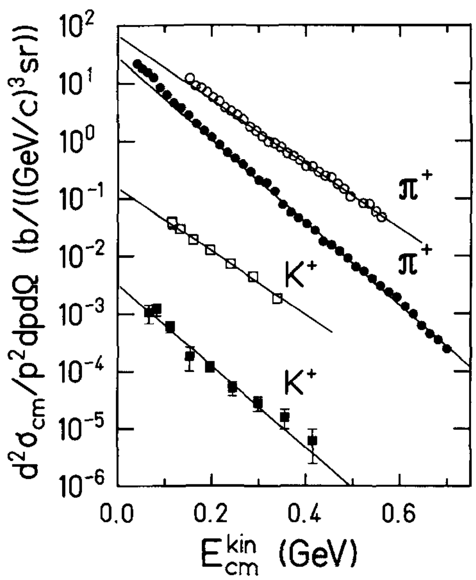

Fig. 2. Differential cross sections for π^+ (circles) and K^+ (squares) as a function of the kinetic c.m. energy measured in Ne + NaF collisions near Θ_{cm} = 90° (see Table 1). Full and open symbols correspond to 1 and 2 GeV/nucleon, respectively. The curves are as in Fig. 1; for pions only the fit to the high energy part is shown (see text).

mass serves as an energy reservoir for K^+ production which is below threshold at a bombarding energy of 1 GeV/nucleon. Hence the production of K^+ mesons is influenced by the abundance and the mass distribution of intermediate baryonic resonances.

The scenario of kaon production via multiple collisions is supported by the experimental finding that the K^+ production probability per participating nucleon increases with the number of participating nucleons [11]. The same conclusion can be drawn from the mass dependence of kaon production. When increasing the masses of the colliding nuclei from A = 20 to A = 197 (at a beam energy of 1 GeV/nucleon), the kaon yield is enhanced by a factor of 120 ± 40 whereas the π^+ yield increases only by 15 ± 5. The high-energy pion inverse slope parameter increases by about δT = 14 ± 3 MeV. These effects can be explained by the higher baryonic density and the larger reaction volume reached in the heavy collision system as compared to the light system. In the dense collision zone of the two Au nuclei the participating baryons undergo a large number of collisions and thus open phase space for the production of high-energy pions and kaons.

The increase of the collision energy from 1 to 2 GeV/nucleon in the Ne + NaF system enhances the K^+/π^+ ratio by a factor of 19 ± 5 and the meson inverse slope parameters by 15–20 MeV (see Table 2). The energy available for particle production in first nucleon–nucleon collisions is increased from 447 to 820 MeV. This favours the population of heavier baryonic resonances which decay into a nucleon and either one high-energy pion or two pions. K^+ mesons can be produced directly via NN → $K^+\Lambda$N, however, only with maximum c.m. kinetic energies of about 150 MeV. The production of kaons with higher kinetic energies (as measured in this experiment and shown in Fig. 3) still requires additional energy from Fermi motion and from multi-step processes involving intermediate baryonic resonances. Therefore, even at 2 GeV/nucleon beam energy the K^+ spectral slope is still influenced by phase space limitations. On the other hand one cannot exclude that K^+ and pions are thermalized after production. In this case, the similar spectral slopes of K^+ and high energy π^+ would reflect the same freeze-out temperature which is most probable the one of the early and dense nuclear fireball.

The measured K^+ inverse slope parameter of T = 79 ± 6 MeV for Ne + NaF at 2 GeV/nucleon is at variance to the high K^+ "temperature" reported previously for Ne + NaF collisions at 2.1 GeV/nucleon by

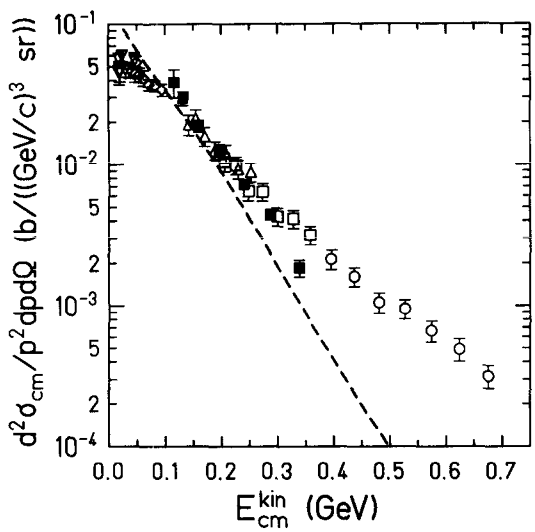

Fig. 3. K^+ cross sections in the c.m. system as a function of the kinetic c.m. energy measured in Ne + NaF collisions. Open symbols: data taken at 2.1 GeV/nucleon beam energy and $15° < \Theta_{lab} < 80°$ [4,12]. Different open symbols represent different values of Θ_{lab}. Full squares: data taken at 2.0 GeV/nucleon and $\Theta_{lab} = 44°$ (this work). Dashed line: QMD calculation for 2.1 GeV/nucleon [19].

Schnetzer et al. [4,12]. These data are shown in Fig. 3 (open symbols) in comparison with our K^+ spectrum taken at 2 GeV/nucleon (full squares). Schnetzer et al. measured K^+ double-differential cross sections at different laboratory angles ($15° < \Theta_{lab} < 80°$) and transformed the data into the nucleon–nucleon c.m. system. The resulting K^+ energy spectrum was fitted by a thermal distribution with a inverse slope parameter of $T = 122$ MeV, assuming isotropic K^+ emission. If the latter assumption is not fulfilled, for example due to K^+ rescattering [21], the K^+ energy distribution as constructed in Ref. [4,12] does not reflect the "temperature" of the reaction zone. The large inverse slope parameter of the K^+ c.m. energy spectrum from Ref. [4,12] may be an artefact of a nonisotropic K^+ angular distribution, with an enhanced K^+ yield at $\Theta_{lab} = 80°$ (open circles, $E^{kin}_{cm} > 0.4$ GeV in Fig. 3) and a reduced yield at $\Theta_{lab} = 15°$ and 25° (open triangles and diamonds, $E^{kin}_{cm} < 0.1$ GeV in Fig. 3). The dashed line in Fig. 3 represents the result of a transport model calculation (QMD) for Ne+NaF at 2.1 GeV/nucleon [19] which agrees well with our K^+ spectrum within the error of the absolute normalization.

In summary, we have presented new data on π^+ and K^+ double differential cross sections measured in Ne+NaF collisions at 1 and 2 GeV/nucleon and compared them to recent results from Au + Au collisions at 1 GeV/nucleon. The data address important aspects of meson production in hot and compressed nuclear matter. The K^+ cross section in nucleus–nucleus collisions at 1 GeV/nucleon depends more than quadratically on the mass of the collision system. This experimental finding favours the picture of subthreshold K^+ production via multiple baryonic collisions. The simple thermal model prediction of different freeze-out temperatures of K^+ and π^+ mesons is not confirmed. The observation of similar slope parameters for K^+ and high energy pions might be a signature for a common freeze-out temperature realized in the early phase of the nuclear fireball.

This work is supported by the German Federal Government (BMBF), by the Polish Committee of Scientific Research (Contract No. PB 201769101) and by the GSI fund for University collaborations.

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