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Production of K^+ Mesons in 2.1 GeV/nucleon Nuclear Collisions

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Abstract

We have measured K^+ meson production by 2.1 GeV/nucleon Ne, d, and p projectiles on NaF and Pb targets. The cross sections depend exponentially upon the kaon energy in the nucleon-nucleon c.m. frame, with an inverse slope T_0 larger than the values obtained from comparable proton and π^- spectra. The angular distribution in this frame is approximately isotropic. We find that $\sigma(\text{Ne+Pb} \rightarrow K^+X)/\sigma(\text{Ne+NaF} \rightarrow K^+X) > \sigma(d+\text{Pb} \rightarrow K^+X)/\sigma(d+\text{NaF} \rightarrow K^+X)$. Existing models do not fit the data well. Possible alternative mechanisms are discussed.

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Recently the study of strange particle (K^+, Λ, K^-) production[1-3] in collisions of relativistic heavy ions has begun. The K^+ mesons are of particular interest since they have an extremely small cross section for absorption and, at low energies, a small cross section, ≈ 13 mb, for scattering on a nucleon. Thus, they may be relatively undistorted by thermalization or multiple scatterings and may, therefore, be more reliable messengers of the early, perhaps very compressed and hot stage of the nuclear collision.

We have measured the inclusive cross section for production of K^+ mesons in collisions of 2.1 GeV/nucleon Ne, d, and p projectiles on NaF and Pb targets. We have compared these data with a simple model based on a superposition of elementary nucleon-nucleon collisions[4]. We find that certain features of the data are not consistent with such a model when conventional internal momentum distributions are assumed. In particular, the number of K^+'s produced with large momentum in the nucleon-nucleon center of mass (NN cms) is much larger than predicted by this model. Also, the dependence of the K^+ production cross sections on the target and projectile masses is not reproduced.

The measurements were made with a magnetic spectrometer which has been described previously[5]. With this spectrometer we identify particles by measuring their rigidity, p/Z, and their time of flight. Since the rate of kaon production in these collisions is approximately a thousand times smaller than that of protons and pions, we employed additional detectors to aid in cleanly selecting the kaons. Pions were vetoed by means of a threshold lucite Cerenkov counter while those protons having relatively large times of flight were rejected by an on-line microprocessor. In addition, a set of Pb-glass blocks were used to identify kaons. Kaons with momentum up to 750 MeV/c stopped in these blocks which then detected the Cerenkov light produced by the kaon decay products. With this apparatus we were able to clearly identify kaons with laboratory momentum between 350 MeV/c and 750 MeV/c. Below 350 MeV/c the corrections for kaon decay become unmanagable, and the acceptance of the spectrometer also deteriorates rapidly. An overall absolute error in the cross section of ≈ 30% is not included in the error bars. Measurements were made at laboratory angles of 15°, 35°, 55°, and 80° by rotating the spectrometer about the target point.

In Figure 1 we plot the non-invariant cross section $d^2\sigma/p^2dpd\Omega$ as a function of the kinetic energy of the kaon (T^*) in the NN cms. For each of the three projectile-target combinations, p+NaF, Ne+NaF, and Ne+Pb, the cross sections for different laboratory angles all tend to lie on an appproximately exponential curve indicating an approximately isotropic angular distribution. However, the inverse slope factor T_0 defined by, $\frac{d^2\sigma}{p^2dpd\Omega} \propto e^{-T^*/T_0}$, is different for the three cases. Its values are: 111 MeV for p+NaF, 122 MeV for Ne+NaF, and 160 MeV for Ne+Pb. For comparison we mention that proton spectra from comparable 2.1 GeV/nucleon collisions are strongly forward-backward peaked[5]. Pion energy distributions are also anisotropic in the nucleon-nucleon cms, although cross sections at small and large cms angles differ at most by a factor of four[5]. In case of Ne+NaF collisions for example the slope factors T_0 for protons and pions vary between ≈ 105 - 115 MeV and ≈ 85 - 95 MeV, respectively, which are thus smaller than for K^+. The dependence of T_0 on projectile and target mass is weaker for protons and pions than for kaons.

Also shown in Figure 1 are data from a different experiment[6] for $pp \rightarrow K^+X$ collisions at 2.54 GeV. These data do not show an exponential behavior. Instead, they are well described assuming that the kaons uniformly occupy all of the available phase space.

The dashed curve in Figure 1 is the result of a calculation[7] for the case of nucleon-nucleon collisions including Fermi motion. A uniform Fermi sphere with a radius equal to p_F = 270 MeV/c was used in the calculation. The calculated ratio of the cross section for production of high energy kaons to that for low energy kaons is 2-3 orders of magnitude lower than the data. Using a Gaussian Fermi distribution with $<p^2> = \frac{3}{5}p_F^2$, instead, changes these results only slightly. This model has been applied also to nuclear collisions by using a row-on-row cascade method[4]. The shape of the spectrum is similar to the dashed curve in Figure 1 and the large disagreement with the data remains.

If scattering of kaons from nucleons[7] is included in these calculations the model predicts more high-energy kaons at large angles, i.e. the calculated kaon momentum distributions in the NN cms fall less steeply than before. However, considerable anisotropy in the NN cms is introduced. Thus, this model does not account for both the production of high energy kaons and the approximate isotropy in the NN cms.

Scattering of kaons from pions has been studied so far only for Ne+NaF under the extreme assumption that a kinetic equilibrium between kaons and pions is established[8]. For this calculation the pions were assumed to be in chemical equilibrium with nucleons and deltas, so that the temperature of the conventional fireball model fully determines the kaon spectra. Because of these assumptions the predicted kaon momentum distribution is isotropic in the c.m. frame. It should be noted, however, that the observed pion spectra are slightly forward-backward peaked. The temperature of the fireball of 115 MeV is compatible with T_0=122 MeV quoted above for Ne+NaF. The kaon production rate is calculated using the row-on-row cascade model[4] and these calculations agree with our data to within a factor of ≈2. It will be interesting to see if a more realistic calculation incorporating the scattering of kaons from both nucleons and pions can reproduce our data.

If one assumes that kaons are in chemical equilibrium with nucleons, pions, etc. the predicted kaon yield for Ne+NaF is larger by a factor of ≈20 than that observed experimentally[9]. A phase space model[10] predicts the right order of magnitude for the cross section at 25° - 35° and small kaon momenta but underestimates the data at larger angles and/or momenta.

Another possible mechanism for producing kaons is through the two-step process $NN \rightarrow \pi X$ followed by $\pi N \rightarrow K^+ X$. The threshold cms energy for the latter reaction is 1.61

GeV. Therefore, only pions with momenta > 900 MeV/c in the laboratory frame will be effective in producing kaons in interactions with (stationary) nucleons. From existing data we estimate that the cross section for the production of pions of this momentum is ≈ 5 mb per NN collision. Then, taking into account the ratio, $\sigma(\pi N \rightarrow K^+X)/\sigma(\pi N \rightarrow \text{anything})$, we estimate that the cross section for kaon production via this mechanism is of the order of 100 μb. This is comparable to the measured cross section for $NN \rightarrow K^+X$ of 50 μb ± 20 μb. We have made a calculation to determine the kinematics of the kaons produced in this two-step process. The inputs to the calculations are the measured pion momentum spectra and angular distributions and the $\pi N \rightarrow K^+X$ cross sections. A uniform Fermi sphere of radius 270 MeV/c was assumed. The result indicates that the kaon energy spectra in the NN cms fall less steeply than before. The reaction rate of this two-step process has also been estimated in a non-equilibrium thermodynamic model[11] and found to be much closer to the observed yield than the results of the thermal model calculation mentioned above.

Another interesting feature of the data is the dependence of the kaon production cross sections on the projectile and target masses. We assume that, for a given projectile the cross section is proportional to $A_T^{\alpha(T^*)}$, where A_T is the mass number of the target. In Figure 2 the values of α are plotted as a function of T^* for both Ne and d projectiles. There is an increase of α with T^* for both types of projectiles. However, the values of α are consistently higher in the case of Ne projectiles than for deuterons. On the basis of simple geometrical considerations only, one would expect that α should be slightly larger for deuteron projectiles than for Ne. However, an incident energy of 2.1 GeV/nucleon, which is only slightly above threshold for kaon production, together with the fact that the average Fermi momentum in a Ne nucleus is higher than that in a deuteron could be a possible cause for the observed behavior of α. Here the reason is that the energy loss of the projectile nucleons as they propagate through the target nucleus reduces their potential for kaon production more rapidly in case of a deuteron projectile as compared to Ne, especially in a heavy nucleus like lead. Of course more exotic mechanisms may also be involved. It is worth noting that the same kind of comparison in the case of pion production shows a similar though smaller effect (see Figure 2).

In summary, we have measured K^+ production for various projectile-target combinations in the momentum region 350 - 750 MeV/c at lab angles 15° - 80°. We have found two features which are not easy to understand on the basis of the models which have been proposed up to now to explain the kaon production: (1) The fact that the cross sections depend exponentially on the kinetic energy of the kaon in the NN cms, and that the angular distribution is almost isotropic in this frame, and (2) the difference in the target A-dependence for Ne and d projectiles. Further measurements of the high energy end of the kaon spectrum ($T^* > 600$ MeV) and a more extensive study of the A-dependence would be helpful in unravelling the mechanisms responsible for kaon production in nucleus-nucleus collisions.

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FIGURE CAPTIONS

Fig. 1 $d^2\sigma/p^2dpd\Omega$ vs. the kinetic energy of the kaon in the nucleon-nucleon center of mass for Ne+Pb→K^+X, Ne+NaF→K^+X, and p+NaF→K^+X. The curves represent fits to an exponential energy distribution (see text). The data of Ref. 6 for 2.54 GeV p+p→K^+X are indicated by a solid line. The result of a calculation[7] for the case of nucleon-nucleon collision including Fermi motion is also shown (dashed curve).

Fig. 2 Target mass dependence of kaons and pions produced in 2.1 GeV/nucleon d+A_T and Ne+A_T collisions. The cross section in the nucleon-nucleon center of mass frame, $\sigma_I = d^2\sigma/p^2dpd\Omega$, has been parameterized for A_T = NaF, Pb as $\sigma_I \propto A_T^{\alpha}$. Shown is α vs. the kinetic energy in that Lorentz frame, T^*. The weak angle dependence of σ_I observed for pions over the kinematical region covered by this experiment, is similar for both targets. Hence, for simplicity, an average value of α has been taken for a given T^*.

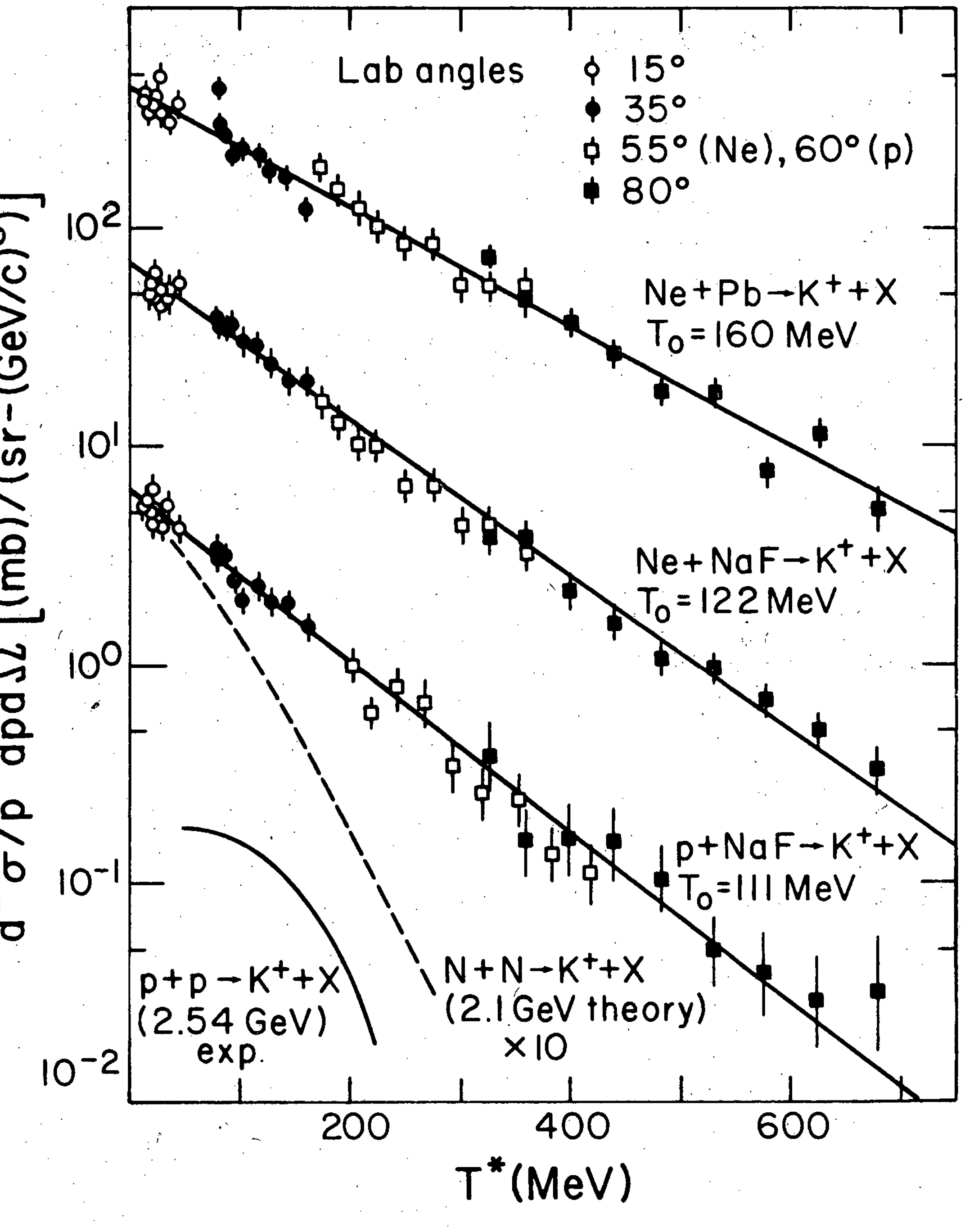

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FIG. 1

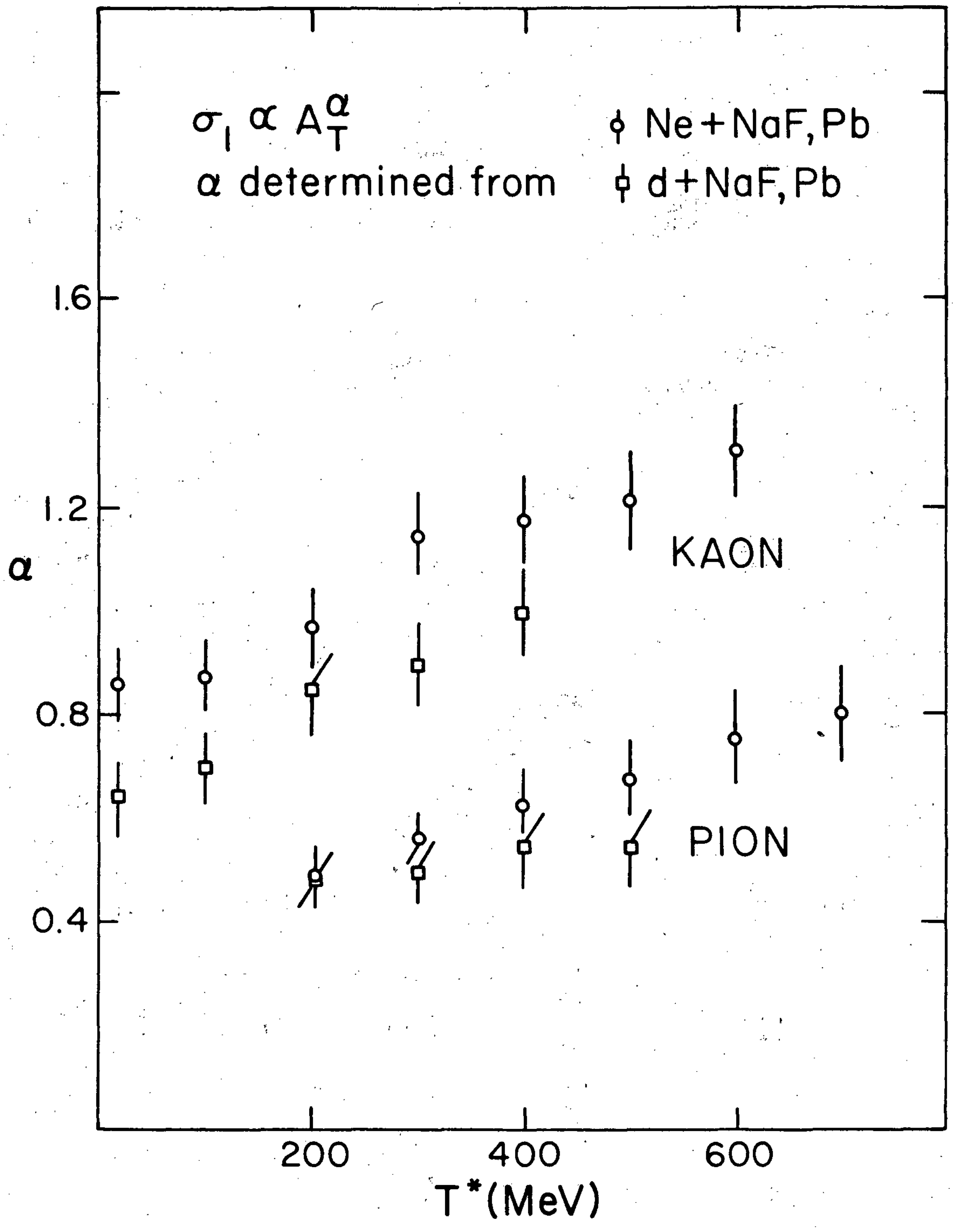

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FIG. 2

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