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

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K^+ meson production by 2.1-GeV/nucleon Ne, d, and p projectiles on NaF and Pb targets has been measured. 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 $\sigma(\mathrm{Ne}+\mathrm{Pb}\rightarrow K^+X)/\sigma(\mathrm{Ne}+\mathrm{NaF}\rightarrow K^+X) > \sigma(d+\mathrm{Pb}\rightarrow K^+X)/\sigma(d+\mathrm{NaF}\rightarrow K^+X)$. Data are compared with theoretical predictions.

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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 system (NN c.m.s.) 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 Cherenkov 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 were stopped in these blocks, and Cherenkov light produced by the kaon decay products was detected. With this apparatus we were able to identify clearly kaons with laboratory momentum between 350 and 750 MeV/c. Below 350 MeV/c the corrections for kaon decay become unmanageable, 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 Fig. 1 we plot the noninvariant cross section $d^2\sigma/p^2 dp\, d\Omega$ as a function of the kinetic energy of the kaon (T^*) in the NN c.m.s. 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 approximately exponential curve indicating an approximately isotropic angular distribution. However, the inverse slope factor T_0, defined by $d^2\sigma/p^2 dp\, d\Omega \propto \exp(-T^*/T_0)$, 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 NN c.m.s., although cross sections at small and large c.m.s. angles differ at most by a factor of 4.[5] In the case of Ne + NaF collisions, for example, the slope factors T_0 for protons and pions vary between ≈ 105 and 115 MeV and ≈ 85 and 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 Fig. 1 are data from a different experiment[6] for $pp \to K^+X$ collisions at 2.54 GeV.

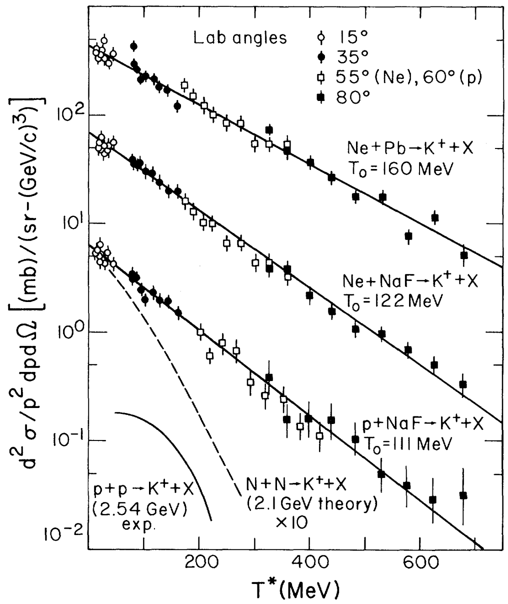

FIG. 1. $d^2\sigma/p^2\, dp\, d\Omega$ vs the kinetic energy of K^+ in the nucleon-nucleon c.m. frame for Ne + Pb → K^+X, Ne + NaF → K^+X, and p + NaF → K^+X. The solid lines represent fits to an exponential energy distribution (see text). The data of Ref. 6 for 2.54-GeV $p+p \to K^+X$ are indicated by a solid curve. The result of a calculation for the case of nucleon-nucleon collision including Fermi motion is also shown (dashed curve).

These data do not show an exponential behavior. Instead, they are well described with the assumption that the kaons uniformly occupy all of the available phase space.

The dashed curve in Fig. 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. The use of a Gaussian Fermi distribution with $\langle p^2 \rangle = \frac{3}{5} p_F^2$ instead, changes these results only slightly. This model has been applied to nuclear collisions by using a row-on-row cascade method.[4] The shape of the spectrum is similar to the dashed curve in Fig. 1 and the large disagreement with the data remains.

In the past, several calculations have been reported, in particular for the Ne + NaF system. Figure 2 summarizes these results. Here, the invariant cross sections are plotted as a function of laboratory momenta of kaons. Figure 2(a) shows the row-on-row cascade results.[4,7] The

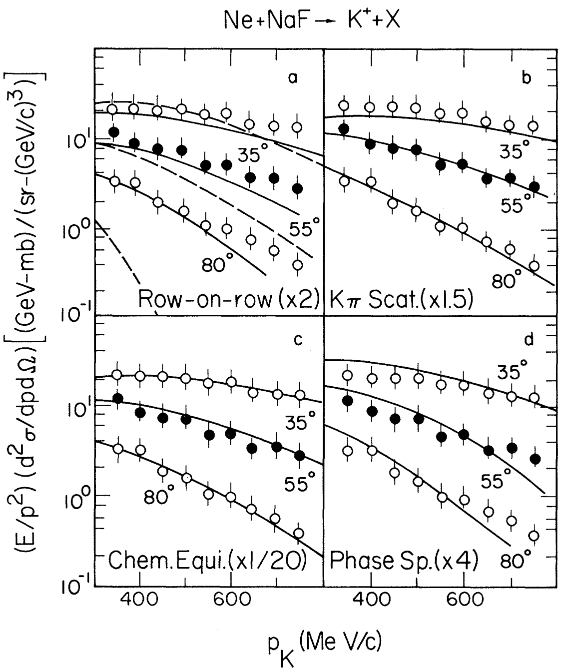

FIG. 2. Invariant cross sections in the laboratory frame as compared with results of various theoretical calculations.

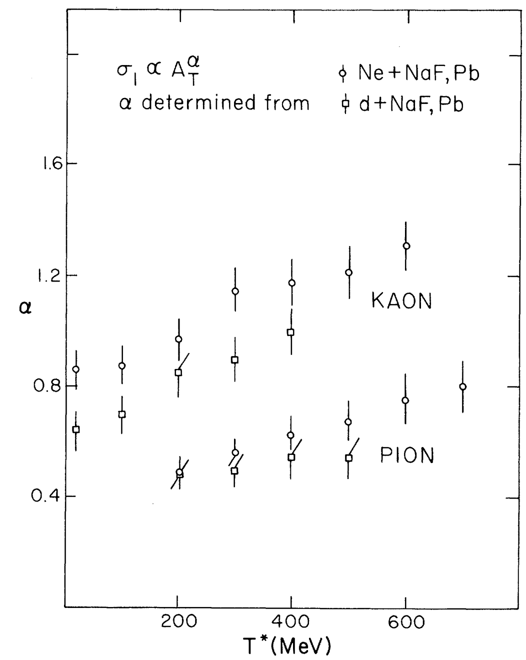

FIG. 3. Observed values of α as a function of the kinetic energy, T^*, in the nucleon-nucleon c.m. frame where α is defined by $\sigma_{\mathrm{inv}} \propto A_T{}^{\alpha}$; $\sigma_{\mathrm{inv}}(\mathrm{proj}+\mathrm{Pb})/\sigma_{\mathrm{inv}}(\mathrm{proj}+\mathrm{NaF}) = (207/21)^{\alpha}$. The observed angle dependence of σ_{inv} for pions, over the kinematical region covered by this experiment, is weak and similar for both targets. Hence, for simplicity, an average value of α has been taken for a given T^*.

dashed curves neglect rescattering of kaons from nucleons (which corresponds to the case mentioned in the preceding paragraph), whereas the solid curves include the effect of these rescatterings. High-energy kaons at large angles are reproduced better by these rescatterings. However, we must notice that if this mode is applied to the case of $p+\mathrm{NaF}$, then considerable anisotropy in the NN c.m.s. is introduced by the rescatterings. Thus, this model does not account for the approximate isotropy in the NN c.m.s. for the $p+\mathrm{NaF}$ system.

Scattering of kaons from pions has been studied under the extreme assumption that a kinetic equilibrium between kaons and pions is established,[8] as shown in Fig. 2(b). 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 itself has been 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] as shown in Fig. 2(c). A phase-space model,[10] Fig. 2(d), gives results very similar to those of row-on-row calculations shown in Fig. 2(a).

Another possible mechanism for producing kaons is through the two-step process $NN \to \pi X$ followed by $\pi N \to K^+ X$. The importance of this process was pointed out by Halemane and Mekjian,[11] although no actual calculations to compare with the observed spectra have been reported.

The last 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. Such a parametrization gives a good fit to the data for a Ne projectile on C, NaF, KCl, Cu, and Pb targets.[1] In Fig. 3 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 for 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. The same kind of comparison in the case of pion production shows a similar though smaller effect.

The real reason for the above observation has not been understood. At an incident energy of 2.1 GeV/nucleon, which is only slightly above threshold for kaon production, the role of Fermi momentum might be important. Then, the average Fermi momentum in a Ne nucleus could be higher than that in a deuteron. Or, the reason may be that the energy loss of the projectile nucleons as they propagate through the target nucleus reduces their potential for kaon production more rapidly in the case of a deuteron projectile as compared to Ne, especially in a heavy nucleus like Pb. There is also an interesting possibility that this is evidence for a collective effect. It may be, for example, that the initial nucleon-nucleon interactions set up some sort of condition such that kaon production in succeeding nucleon interactions is enhanced. The present data, however, do not allow us to make any definite statement.

In summary, we have measured K^+ production for various projectile-target combinations in the momentum region 350–750 MeV/c at laboratory 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 c.m.s., 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 unraveling the mechanisms responsible for kaon production in nucleus-nucleus collisions.

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