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Energy Spectrum of Subthreshold K^- Produced in Relativistic Nuclear Collisions

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ABSTRACT

K^- production at 0° has been measured for the reaction ^{28}Si + ^{28}Si at 2.1 GeV/nucleon. The energy dependence of the K^- production cross section is given approximately by $(E/p^2) d^2\sigma/dpd\Omega =$ 3.9 exp $(-E^*/91)$ mb-GeV/sr-(GeV/c)^3 where E^* is the kaon kinetic energy in the nucleus-nucleus center of mass. A total K^- production cross section of 1.0± 0.2 mb is obtained by assuming an isotropic angular distribution in the center of mass. Possible mechanisms for subthreshold production are discussed.

Relativistic nuclear collisions may demonstrate interesting and exotic nuclear phenomena involving abnormally dense nuclear matter,[1] meson condensation,[2] or a phase transition to the quark-gluon plasma.[3] For these effects to occur, some degree of equilibration or collective interactions among the colliding nucleons must take place. A straightforward indication of thermal or collective behavior is the creation of particles whose production threshold is significantly above the available nucleon- nucleon collision energy. At the maximum Bevalac kinetic energy of 2.1 GeV/nucleon, the lightest particle for which production is "subthreshold" is the K^-. Production of a K^- in N-N collisions requires bombarding energies greater than 2.5 GeV. Our observation of K^- produced at 1 GeV/c and 0° in Si+Si collisions at 2.1 GeV/nucleon has been reported previously.[4]

We have extended our study of subthreshold kaon production by measuring the momentum distribution of K^- produced at 0° in the reaction ^{28}Si + ^{28}Si at 2.1 GeV/nucleon. As in our previous measurement,[4] negative secondaries produced in the heavy ion collisions were momentum selected and transported along a magnetic beam line. An arrangement consisting of three bends, each followed by a detector station at a focus, allowed for multiply redundant measurements and particle identification. Each detector station was instrumented with an array of scintillation counters and Cerenkov counters. Particle mass and charge were determined from time of flight and dE/dx measurements and the known rigidities. Suppression of the dominant pion background was made with focusing liquid Cerenkov counters for secondary momenta less than 1 GeV/c and with high pressure gas Cerenkov counters for secondary momenta greater than 1 GeV/c.

We measured yields of K^- at laboratory momenta of 0.63, 0.73, 0.90, 1.42, 1.92 and 2.37 GeV/c. The actual numbers of kaons extracted from the data were 2, 10, 17, 17, 10 and 21 respectively. These momenta correspond to kinetic energies in the nucleus-nucleus center-of-mass frame of 4, 15, 49, 192, 353 , and 523 MeV. The invariant K^- cross section plotted as a function of this kinetic energy is shown in figure 1, which also includes the result of our previous measurement at $p_{lab} = 0.98$ GeV/c, or $E^* =$ 66 MeV. The data are well described by an exponential with a slope parameter E_0 of 91$\pm$ 7 MeV (solid line in figure 2). If we assume that the K^- production is isotropic in the nucleus-nucleus center of mass frame, integration over production energy and angle yields a total K^- cross section of 1.0$\pm$ 0.2 mb for Si+Si at 2.1 Gev/nucleon.

These results for K^- production can be compared to those reported for K^+ production in relativistic nuclear collisions. Schnetzer et al.[5] have measured K^+ yields at laboratory angles ranging from 15° to 80° in the reaction Ne+NaF at 2.1 GeV/nucleon. Note that this bombarding energy is well above the threshold for production of K^+ in N-N collisions. Their results suggest isotropic production in the nucleus-nucleus center-of-mass frame, with a slope parameter of 140 MeV. The smaller value which we report for E_0 in K^- production may be due to the shorter mean free path for K^- in nuclear matter ($\sim$ 2 fm as compared to $\sim$ 7 fm for K^+). This would tend to dilute the primordial momentum spectrum of the K^- to a greater extent than for the K+. The reported total cross sections extrapolated for K+ production in Ne+NaFl is 23 mb. Applying A_pA_t scaling to this result, we estimate the K^-/K^+ production ratio in our reaction to be approximately 1/45.

An exponential spectrum may indicate a thermal source for kaons produced in the mid-rapidity region. Barz et al.[6] have published calculations invoking a "hadrochemical" model which predict a total K^- yield

at approximately the level reported here. Their calculations also reproduce the total K^+ yield and the pion yields at various bombarding energies. Their model assumes that the hadrons are thermalized, and considers the time evolution of the hot hadronic gas which includes particle production and annihilation. The agreement of their model with our data further supports arguments for a thermal mechanism for K^- production. However, recent results from the Plastic Ball for $^{40}Ca + ^{40}Ca$ at 400 MeV/nucleon and at 1.0 GeV/nucleon show that only a small fraction of detected protons can be the result of an isotropic source in the mid-rapidity region.[7] This result makes it seem unlikely that equilibration can occur in a system as small as Si+Si at 2.1 GeV/nucleon.

Several other possible mechanisms may account for subthreshold K^- production. At 2.1 GeV/n, nuclear collisions consist primarily of independent N-N interactions, since the de-Broglie wavelengths of the incoming projectile nucleons are much smaller than the mean internucleon separation. Although for N-N collisions 2.1 GeV is below the K^- production threshold, the nuclear Fermi momentum of the projectile and target nucleons allow more of the bombarding energy to be used for excitation rather than translational energy. To estimate this effect, we have performed a Monte-Carlo calculation which contains internal nuclear momentum for the colliding nucleons, and assumes particle production proportional to the available phase space. With a double-Gaussian parameterization for the internal nuclear momentum,[18] we were able to obtain excellent agreement with existing data for subthreshold anti-proton production in p-nucleus collisions.[8] We apply this calculation to our K^- data by obtaining the normalization for K^- production from our measurement for p+Cu at 4.8 GeV and by assuming an A_pA_t scaling. Effects of nuclear absorption are expected to be large but should be comparable for $^{28}Si + ^{28}Si$ and for $p + ^{63}Cu$. We underpredict the observed K^- yield by approximately a factor of 20. A recent calculation by W. Zwermann and B. Schurmann incorporating the Fermi momentum of the colliding nucleons appears to account for a sizable fraction of the observed K^- yield.[19] This calculation assumes a weak energy dependence which agrees with p-p data at relatively larger energies but for which no data exists for energies close to threshold. Their calculation also does not adequately take into account nuclear K^- absorption.

Recently C.M. Ko[16] has suggested that hyperon-pion strangeness exchange interactions may contribute significantly to K^- production rates. His calculation assumes a thermal distribution of pions, with a temperature of 135 MeV, which interact with hyperons produced above threshold. This assumed pion temperature is almost twice that observed in nuclear collisions at 2.1 GeV/nucleon. This gives rise to an artificially high kaon yield since the reaction π-Y $\rightarrow K^-$ N is an endothermic one. In addition his calculation does not take into account the finite lifetime of the Δ which tends to suppress the pion-hyperon interaction. Ko has also argued that the K^- spectrum is significantly influenced by K-N rescattering through the $\Lambda(1520)$ resonance. However, the narrowness ($\sim$15 MeV) of this resonance makes it unlikely that many K^-N interactions proceed through this channel.

With the present K^- data, we are able to rule out the Φ-bremsstrahlung model proposed by K. H. Muller.[17] In his model, Φ mesons are radiated by decelerating nuclear matter and decay to K^- sharply peaked at mid-rapidity. This results in a spectrum steeper than that observed. The mechanism of K^+K^- condensation[2] also seems unlikely since it would give rise to a peak in the K^- momentum spectrum, presumably at the C.M. momentum where K^- nucleon attraction is strongest.

Recent experiments on deep inelastic muon[8] and electron[9] scattering report systematic differences between the structure functions in iron and deuterium (EMC effect). These results indicate a distortion in the structure functions of nucleons embedded in a nucleus that cannot be attributed to Fermi momentum. Several theoretical models suggest that these differences may be due to the existence of 6-quark and 9-quark bags in nuclei.[10,11,12] The EMC effect may also indicate a larger distribution of sea quarks in nuclei. This would have a marked effect on K^- production which proceeds mostly by the fusion of an s and a u quark, both from the sea. An enhancement of sea quarks in nuclei would thus result in large K^- yields in nucleus- nucleus collisions as compared to N-N collisions.

We conclude that subthreshold K^- production in relativistic nuclear collisions is observed at a level greater than that expected on the basis of individual nucleon-nucleon collisions. The K^- momentum spectrum is approximately exponential, suggesting a thermal mechanism, possibly as a result of hyperon-pion strangeness exchange reactions[16] or kinetic equilibrium among the participant nucleons.[6] This exponential slope rules out several other production mechanisms and the total yield is unlikely to be explainable as being due to nuclear Fermi momentum or intermediate rescattering collisions. The relatively large K^- yield ($\sim$1 mb) may also be an indication of a collective phenomenon such as extended quark bags, or an effect of the high densities achieved in nuclear collisions.

References

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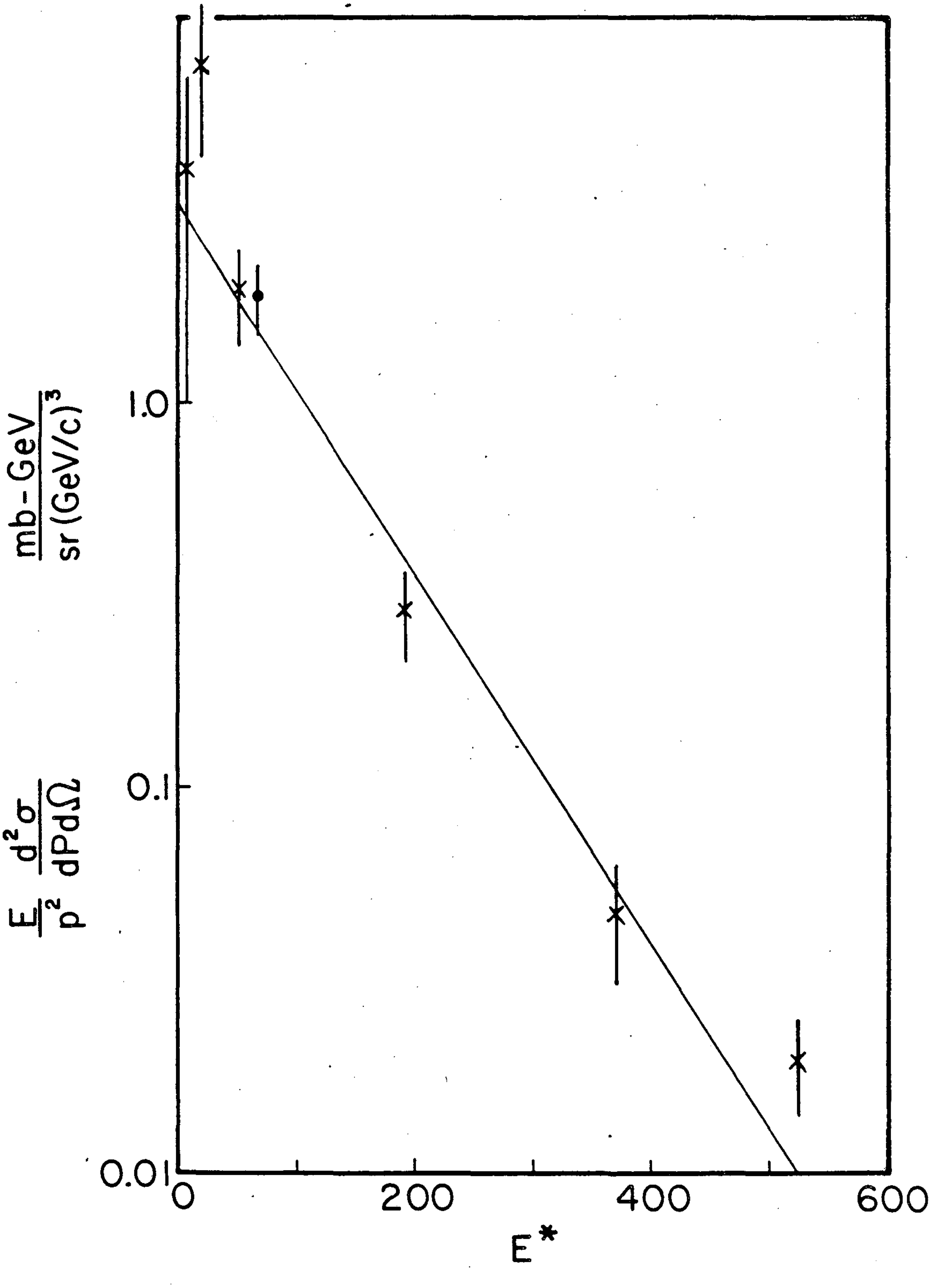
Figure Captions

Figure 1. Invariant cross section for the production of K^- at 0° in Si+Si at 2.1 Gev/nucleon as a function of the K^- kinetic energy in the nucleus-nucleus center of mass frame. The solid line represents a fit to an exponential with a slope parameter of 91 MeV.



$\frac{E}{p^2} \frac{d^2\sigma}{dPd\Omega}$ $\frac{mb-GeV}{sr(GeV/c)^3}$
1.0
0.1
0.01
0
200
400
600
E*

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