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Author
Barasch, E.

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K⁻ Momentum Spectrum for Subthreshold Production in Relativistic Nuclear Collisions

E. Barasch, (a) A. Shor, (a,b) S. Abachi, (b) J. Carroll, (b) P. Fisher, (a) K. Ganezer, (b) G. Igo, (b) T. Mulera, (a) V. Perez-Mendez, (a) and S. Trentalange (b)

(a) Nuclear Science Division, Lawrence Berkeley Laboratory,
University of California, Berkeley, CA 94720

and

(b) University of California, Los Angeles, CA 90024

and

(c) University of California, Davis, CA 95616

Abstract

K⁻ production at 0° has been measured for the reaction $^{28}\text{Si} + ^{28}\text{Si}$ at 2.1 GeV/nucleon. The K⁻ cross section is given approximately by $(E/P^2)d^2\sigma/dPd\Omega = 3.9e^{-E/91}\text{mb GeV}/sr - \text{GeV}/c$ where $E^*$ is the K⁻ kinetic energy in MeV in the nucleus-nucleus center of mass. A total K⁻ cross section of $1.0 \pm 0.2 \text{ mb}$ is inferred for isotropic production. Mechanisms for subthreshold production are discussed.

Relativistic nuclear collisions (RNC) may demonstrate interesting and possibly exotic nuclear phenomena involving abnormally dense nuclear matter, (1) meson condensation, (2) or a phase transition to a quark-gluon plasma. (3) For these nuclear 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 energy of 2.1

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*Present address: Brookhaven National Laboratory, Upton, NY 11973.
†Present address: California Institute of Technology, Pasadena, CA 91125.
‡Present address: University of California, Irvine, CA 92717.
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GeV/nucleon, the lightest particle for which production is "subthreshold" is the $K^-$. Production of $K^-$ in N-N collisions requires bombarding energies greater than 2.5 GeV. Previously, we have reported our observation of $K^-$ production at 1GeV/c and 0° in Si + Si collisions. (4)

We have extended our study of subthreshold $K^-$ production by measuring the momentum distribution for $K^-$ produced at 0° in the reaction $^{28}$Si + $^{28}$Si at 2.1 GeV/nucleon. 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 waist, allowed for multiply redundant measurements and particle identification. The detector stations were instrumented with an array of scintillation counters and Cerenkov counters. Particle mass and charge were determined from the time of flight and dE/dX measurements and the known rigidities. Identification of the dominant pion background was made with focusing liquid Cerenkov counters for $P < 1$ GeV/c and with high pressure gas counters for $P > 1$ GeV/c.

As an example of the good particle separation in our data, we show in figure 1 the results for the highest measured laboratory momentum of 2.4 GeV/c. The solid curve gives the TOF distribution for events that registered at the first two detector stations but did not trigger either of the gas Cerenkov counters. The data set represents approximately 60,000 events prior to the Cerenkov cuts. The events in the TOF peak at 0.85 ns are identified as kaons. Four events contained information from the third detector station which confirmed that these events were kaons. Cross sections were determined by taking into account kaon and pion decay, channel acceptance, target thickness, and integrated projectile flux.

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 invariant $K^-$ cross section, plotted as a function of the $K^-$ kinetic energy in the nucleus-nucleus center-of-mass frame, is shown in figure 2. The result of
our previous measurement at $P_{lab} = 0.98 \text{ GeV/c}$ is also included in the figure. The data are well described by an exponential with a slope parameter $E$ of $91 \pm 7 \text{ MeV}$ (solid line in figure 2). If we assume that the $K^-$ production is isotropic in this reference frame, we extract a total $K^-$ yield of $1.0 \pm 0.2 \text{ mb}$ for $\text{Si} + \text{Si}$ at $2.1 \text{ GeV/n}$. This assumption is reasonable for particle production which is peaked at the mid-rapidity.

The exponential spectrum for the kaons may indicate a thermal source at the mid-rapidity region. Barz et al.\textsuperscript{(5)} have published calculations invoking the "hadro-chemical" model which predicts a total $K^-$ yield at approximately the level reported here. Their model assumes that the hadrons are thermalized, and considers the time evolution of the hot hadronic gas which includes particle production and annihilation. This further supports arguments for a thermal mechanism for the $K^-$ production. However, recent results from the Plastic Ball for $\text{Ca} + \text{Ca}$ at $400 \text{ MeV/n}$\textsuperscript{(6)} show that only a small fraction of events result in an isotropic distribution for the detected protons with respect to the mid-rapidity region. It seems, therefore, unlikely that equilibration occurs for a system as small as $\text{Si} + \text{Si}$ at $2.1 \text{ GeV/n}$.

Several models have been studied in an effort to account for the observed high $K^-$ yield. At $2.1 \text{ GeV}$, the deBroglie wavelengths of the incoming projectile nucleons are about $0.3 \text{ Fermi}$, certainly much smaller than the mean internucleon separation. It is therefore reasonable to assume that the nuclear collisions consist of independent $N-N$ interactions. Although $N-N$ collisions at $2.1 \text{ GeV}$ are below the $K^-$ production threshold, the nuclear Fermi momentum of the projectile and target nucleons allows for more of the $N-N$ bombarding energy to be used for excitation rather than translational energy. A calculation has been performed\textsuperscript{(4)} which assumes a double gaussian parameterization for the internal nuclear momentum. Although very good agreement was obtained for data on subthreshold anti-proton production in proton nucleus collisions,\textsuperscript{(7)} calculations for $K^-$ production in nucleus-nucleus collisions predicted rates twenty times lower than those observed in this experiment.
Recent experiments on deep inelastic muon\(^{8}\) and electron\(^{9}\) scattering report systematic differences between the structure functions in iron and deuterium. 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.\(^{10,11,12}\) This effect would change our picture of independent N-N collisions and would have a marked effect on subthreshold production. We have made calculations for \(K^-\) production assuming that 30% of the nuclear matter resides in 6 quark bags. Such an assumption enabled Carlson et al.\(^{11}\) to qualitatively account for the variations in the structure function for iron. With the assumption of "universality" in hadron production,\(^{13}\) we are able to reproduce the observed \(K^-\) yield.

The "EMC" results 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 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 p-p collisions.

We have made an estimate for the effects of intermediate \(\pi N, NN, N\Delta\) and \(\Delta\Delta\) interactions on \(K^-\) production in nucleus-nucleus collisions. Calculations using the distributions for hadron-hadron center of mass energies extracted from a cascade calculation\(^{14}\) convoluted with \(K^-\) production cross sections\(^{15}\) show that these effects contribute less than 10% of the observed yield. Recently C.M. Ko\(^{16}\) has shown that hyperon-pion strangeness exchange interactions contribute significantly to the \(K^-\) production rates. However, his calculations assume thermal pions, and do not take into account finite lifetimes for the \(\Delta\) or the resonant production of hyperons. We estimate that these effects will reduce the calculated yield to approximately 20% of the observed yield.
With the present $K^-$ data, we are able to rule out the $\varphi$-Bremsstrahlung model proposed by K. H. Muller. In his model, $\varphi$-mesons are radiated by the decelerating nuclear matter and decay to $K^-$ sharply peaked at mid-rapidity. The mechanism of $KK^-$condensation also seems unlikely since it would imply a structure in the $K^-$ momentum spectrum, presumably at a c.m. momentum where $K^-$ nucleon attraction is strongest.

We conclude that the subthreshold $K^-$ production observed in relativistic nuclear collisions is at a level above 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 (C. M. Ko) or kinetic equilibrium among the participant nucleons (Barz et al.). The relatively large $K^-$ yield ($\sim$1 mb) may also be an indication of a collective phenomenon or an effect of the high densities achieved in nuclear collisions.

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Figure Captions

Figure 1. Si + Si $\rightarrow$ negatives at $P_{\text{lab}} = 2.37$ GeV/c and $0^\circ$. Data sample contains $6 \times 10^6$ events prior to Cerenkov cuts. Peak at 0.85 ns identified as K$^-$ by mean TOF.

Figure 2. Si + Si at 2.1 GeV/n $\rightarrow$ K$^-$ at $0^\circ$. Plotted in nucleus-nucleus center of mass frame. Solid line represents best fit for $\sigma \propto e^{-E\sqrt{E_0}}$. 
Figure 2
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