# Measurement of "Subthreshold" Production of $K^-$ and Antiprotons in Relativistic Nuclear Collisions

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The observation of subthreshold production of $K^-$ in the reaction $^{28}\text{Si} + ^{28}\text{Si}$ at 2.1 GeV/nucleon is reported. For production at $0°$ and 1 GeV/$c$, a $K^-$ cross section ($d^2\sigma/dp\,d\Omega$) of 1.6 mb sr$^{-1}$ (GeV/$c$)$^{-1}$ and an upper limit for $\bar{p}$ production of 3 nb sr$^{-1}$ (GeV/$c$)$^{-1}$ were measured. Calculations incorporating the effect of nuclear Fermi momentum underpredict the $K^-$ yield by more than a factor of 20. Production mechanisms involving collective effects and equilibration are discussed.

The study of relativistic nuclear collisions (RNC) offers the possibility of investigating the properties of nuclear matter at high densities and temperatures.[1] It has been suggested that at such densities and temperatures a variety of exotic nuclear phenomena (including the existence of abnormally dense nuclear states,[2] meson condensation,[3] and phase transitions to quark matter[4]) may occur. For such effects to occur in RNC, some degree of equilibration or collective interaction among the colliding nucleons must take place. \No conclusive evidence has yet been found for such interactions in nuclear reactions at the highest available energies. This may be due in part to the possibility that these processes rarely occur, and in part to the difficulty of establishing a signature for their identification. A clear experimental signature for collective or thermal effects in RNC would be the observation of particles whose production threshold is at an energy significantly larger than that available in individual nucleon-nucleon collisions. This "subthreshold" particle production offers several advantages for probing nuclear effects at high en-

ergies; the yields from conventional sources (i.e., independent $N$-$N$ collisions) are small by definition, and final-state interactions do not obscure the results because it is the very existence of the observed particles which is of significance.

Recently, subthreshold production of pions in nuclear collisions has been reported for $^{12}\text{C} + ^{12}\text{C}$ at 85 MeV/nucleon[5] and for $^{20}\text{Ne} + \text{NaF}$ at slightly higher energies.[6] The yields of pions in these measurements, however, appear to be consistent with production by independent collisions of nucleons with internal nuclear momenta. A recent experiment[7] has demonstrated coherent production of pions in the reaction $^3\text{He}(^3\text{He}, \pi^+)^6\text{Li}$ at about 90 MeV/nucleon. Such coherent production is unlikely at energies of a few GeV/nucleon where the de Broglie wavelength of the colliding nucleons is much smaller than the internucleon separation.

We have conducted a search for subthreshold production of $K^-$ and antiprotons in the reaction $^{28}\text{Si} + ^{28}\text{Si}$ at an incident energy of 2.1 GeV/nucleon.[8] A schematic of the experimental layout is shown in Fig. 1. Negative secondaries produced
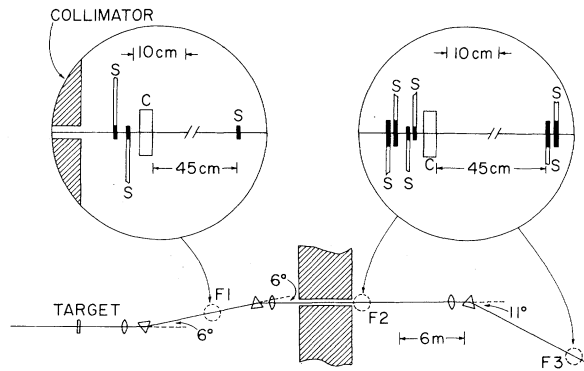
FIG. 1. Experimental layout: Schematic of magnetic beam line following production target. Magnetic elements are represented by prisms for bending and lenses for focusing elements. Insets of detector stations contain scintillation (S) and Cherenkov (C) counters.



FIG. 2. Relative time of flight between F1 and F2 for negative secondaries produced at 1 GeV/$c$ and 0° by $^{28}$Si + $^{28}$Si collisions at 2.1 GeV/nucleon. Data set contains $4 \times 10^6$ events prior to the Cherenkov cuts. Pion and proton peaks (dashed curves) determined from data on positives.

at 0° in the 23-g/cm$^2$ metallic target were momentum selected and transported along a magnetic beam line (acceptance $d\Omega \sim 0.8$ msr, $\Delta p/p \sim 3\%$). The central momentum was chosen to be 1 GeV/$c$, which corresponds to the laboratory momentum of antiprotons produced at rest in the center of mass. For these kinematic conditions the threshold in $N$-$N$ collisions is 5.63 GeV for the production of $\bar{p}p$ pairs and 2.77 GeV for $K^-K^+$ pairs. Detector stations, each consisting of an array of scintillators and a focusing Cherenkov counter,[8,9] were placed at three locations to provide multiply redundant particle identification. Timing and pulse-height data from all detectors were digitized and recorded on magnetic tape for each event. An event was defined by the trigger electronics as an inclusive OR of several minimally restrictive requirements on flight times or Cherenkov pulse heights. In addition to the data from the Si + Si reaction, data were acquired for the reaction $p$ + Cu with the same beam-line and electronics settings. These data provided various checks and calibrations of system performance. Positive particles ($p$, $K$, $\pi$) were measured at an incident proton energy of 2.1 GeV, and negative particles were measured at a proton energy of 4.8 GeV.

The data set of negative secondaries from $^{28}$Si + $^{28}$Si at 2.1 GeV/nucleon contains four million events that satisfy geometry-defining requirements at the first two detector stations. The time-of-flight (TOF) spectrum, after imposing requirements on Cherenkov pulse height to suppress the dominant pion component, is shown in
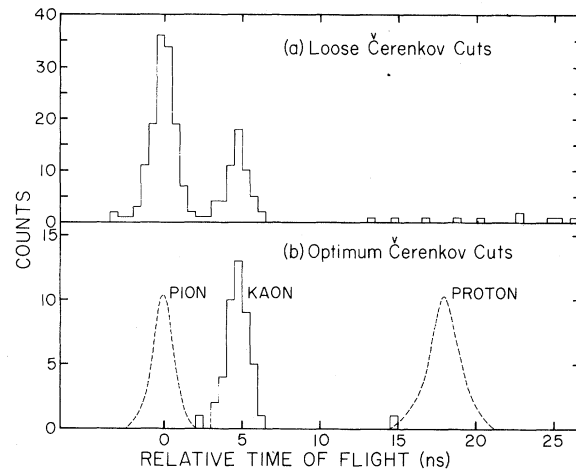
Fig. 2. The events in the peak at 5 ns are identified as kaons by their mean TOF and by the observation that the correct fraction survives to the third detector station and produces appropriate signals there. [Figure 2(a), with moderately restrictive requirements on C pulse heights, shows distinct pion and kaon peaks. Figure 2(b), with more stringent C cuts, shows that the pion peak is eliminated with only a 15% loss of kaons.] After correcting for decay and absorption along the 27-m flight path and for the effects of attenuation in the thick target, we obtain a $K^-/\pi^-$ ratio of $(3.2 \pm 0.5) \times 10^{-4}$ corresponding to a cross section for $K^-$ of $d^2\sigma/dp\, d\Omega = 1.65 \pm 0.54$ mb sr$^{-1}$ (GeV/$c$)$^{-1}$. In contrast, for $p$ + Cu at 4.8 GeV, we obtained a $K^-$ cross section of $d^2\sigma/dp\, d\Omega = 1.33 \pm 0.33$ mb sr$^{-1}$ (GeV/$c$)$^{-1}$ at 0° and 1 GeV/$c$.

The one event in Fig. 2(b) with a TOF close to that of an antiproton registered $dE/dx$ signals in the scintillation counters inconsistent with those observed for protons in the run with positive secondaries. We arrive at an upper limit for antiprotons of $\bar{p}/\pi^- < 6 \times 10^{-7}$ and $d^2\sigma/dp\, d\Omega < 3$ nb sr$^{-1}$ (GeV/$c$)$^{-1}$ for production at 1 GeV/$c$ and 0° (with 90% confidence level).

The significance of the $K^-$ yield from nucleus-nucleus collisions has been evaluated by comparing it to the yields expected on the basis of models which do not include thermal or collective effects. In the first of these calculations the $K^-$ are assumed to be produced directly from in-

dividual nucleon-nucleon collisions. The model
assumes that nuclear collisions consist only of
such collisions, but also includes an internal
momentum distribution which accounts for sub-
threshold production in $p$-nucleus collisions. The
model considers only first-encounter collisions
and assumes that particle production is propor-
tional to the available phase space with a transi-
tion matrix element that is independent of energy.
This calculation is similar to those discussed by
Dorfan et al.[10,11] For the internal momentum
distribution of nucleons within the nucleus we
have adopted a double Gaussian parametrization
successfully employed by Geaga et al.[12] for fitting
spectra of protons produced at 180° in various
reactions. The width and relative magnitude of
the term describing the higher momentum com-
ponents is taken from this parametrization, and
the width of the dominant term is taken from
electron scattering data as reported by Moniz
et al.[13] We find that this scheme closely re-
produces the energy dependence of the data[10] on
subthreshold production in $p + Cu \rightarrow p$ (see Fig. 3)
and in $p + Be \rightarrow K^-$.[15] This excellent agreement
gives us confidence in the ability of our calcula-
tions to describe nucleon-nucleon collisions that
occur within the nuclear medium.



FIG. 3. $p + Cu \rightarrow \bar{p} + X$ antiproton cross sections ob-
tained by multiplying $\bar{p}/\pi^-$ ratios from Dorfan et al.
(Ref. 10) by pion cross sections from Papp (Ref. 14).
Curve represents calculations employing a double
Gaussian parametrization for the internal nuclear mo-
mentum distribution.

To apply this calculation to our measurement of $K^-$ production from Si + Si collisions we define a
quantity, $R$, in which the unknown matrix element no longer appears:

$$R = \frac{1}{A_p A_T} \frac{d^2\sigma}{dp\, d\Omega} ({}^{28}\text{Si} + {}^{28}\text{Si} \rightarrow K^- \ (2.1 \ \text{GeV/nucleon})) \left[ \frac{1}{A_p A_T} \frac{d^2\sigma}{dp\, d\Omega} (p + Cu \rightarrow K^- \ (4.8 \ \text{GeV})) \right]^{-1},$$

where $A_p$ $(A_T)$ is the mass number of the indi-
cated projectile (target), and the yields are at
1 GeV/$c$ and 0° in the laboratory. We find that
$R_{\text{meas}} = 0.1 + 0.03$ which is 20 times larger than
the calculated results, $R_{\text{calc}} = 0.0045$. This dis-
crepancy becomes even larger if the yield is
proportional to some lower power of the nucleon
numbers, as might be expected on the basis of
nuclear shadowing and projectile energy degrada-
tion.

An estimate has also been made of the yield of
$K^-$ produced through the sequential reactions
$NN \rightarrow \pi X$, $\pi N \rightarrow K^- X'$ where both steps occur
within the same nucleus. A calculation based on
measured pion yields in nuclear collisions[16] and
measurements of $\pi N \rightarrow K^- X$ cross sections[17] re-
sults in a yield that is less than one tenth of the
observed rate. Similar estimates of $K^-$ produc-
tion through intermediate strange baryons also
result in yields smaller than that observed.

The calculations described above, while not
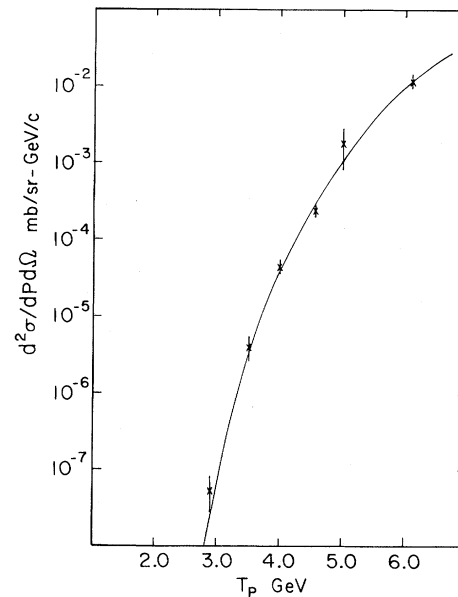definitive, should give reasonably conservative

estimates of the $K^-$ yield expected from models
of simple $N$-$N$ interactions. The size of the dis-
crepancy between the calculated and observed
yields suggests that more complicated phenom-
ena may be required in the production process.
Fireball models which assume complete thermal-
ization of the participating nucleons provide one
natural framework in which subthreshold produc-
tion can occur. The simplest models which
assume both chemical and kinetic equilibrium
of rarely produced particles predict yields of
rare particles much larger than observed. Cal-
culations based on the work of Olive[18] give [for
a fireball temperature of 110 MeV (Ref. 19)]
ratios of $K^-/\pi^- \sim 1.7 \times 10^{-2}$ and $\bar{p}/\pi^- \sim 6 \times 10^{-6}$ for
thermally produced particles in our kinematic
region. These values are a factor of 60 larger
than our measured $K^-/\pi^-$ ratio and a factor of
10 above our $\bar{p}/\pi^-$ upper limit. A similar model[20]
predicts $K^+$ yields in nuclear collisions approxi-
mately 20 times larger than those observed.[16]

Preliminary calculations employing nonequilibrium thermodynamics[21] do appear to be in agreement with the observed yields.

Subthreshold production is also predicted by a number of models which require collective (but nonthermal) interaction among the participants. The collective tube model,[22] which assumes that strings of nucleons contribute coherently to the available production energy, predicts an antiproton yield roughly a hundred times larger than our measured upper limit. Muller[23] has suggested that the observed kaons may be produced by the decay of $\varphi$ mesons which exist as virtual particles in the colliding nuclei and are radiated during the strong deceleration of the collision. Berenzovoi et al.[24] have speculated about "an anomalously large yield of strange mesons" from "heavy-ion collisions at energies of order 1 GeV/nucleon" produced by the decay of a $K\bar{K}$ condensate occurring at 2–6 times normal nuclear density. Nuclear matter at densities higher than normal may also provide other mechanisms which enhance subthreshold production, e.g., as a result of very large internal momentum components, or through a substantial reduction of the mass of the produced particle in the presence of large attractive potentials.

The copious production of $K^-$ observed in the collision of $^{28}$Si + $^{28}$Si at 2.1 GeV/nucleon appears to be appreciably beyond the levels expected on the basis of simple nucleon-nucleon interactions. Several models which involve equilibration of the colliding nuclear system or collective multinucleon processes predict subthreshold $K^-$ production in RNC. Further measurements are needed to determine the specific production mechanism.

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