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A 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 $^{28}Si + {}^{28}Si$ at 2.1 GeV/nucleon is reported. For production at 0° and 1 GeV/c, a K^- cross section $(d^2\sigma/dpd\Omega)$ of 1.6 mb/sr-GeV/c, and an upper limit for $\bar{p}$ production of 4 nb/sr-GeV/c were measured. Calculations which incorporate a nuclear momentum distribution for the colliding nucleons predict a K^- yield less than one twentieth of that observed. Possible mechanisms for subthreshold production 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 energies; 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.

We have conducted a search for subthreshold production of K^- and antiprotons in the reaction $^{28}Si + ^{28}Si$ at an incident energy of 2.1 GeV/nucleon[5]. A schematic of the experimental layout is shown in Fig. 1. Negative secondaries produced at 0° in the 23 g/cm^2 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 NN 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 focussing Cherenkov counter[5,6], 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 + ^{68}Cu with the same beam-line and electronics settings. These data provided various checks and calibrations of system performance. Positive particles (p, K, π) 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 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. After correcting for decay and absorbtion along the 27m flight path and for the effects of attentuation in the thick target, we obtain a K^-/π^- ratio of

$3.2 \pm 0.5 \times 10^{-4}$ corresponding to a cross section for K^- of $d^2\sigma/dpd\Omega = 1.65 \pm 0.54$ mb/sr/GeV/c. In contrast, for $p + {}^{63}Cu$ at 4.8 GeV, we obtained a K^- cross section of $d^2\sigma/dpd\Omega = 1.33 \pm 0.33$ mb/sr/GeV/c at 0° and 1 GeV/c. (The error quoted for the Si + Si cross section contains a systematic error due to thick target corrections whose limits are given by 1 ± 0.17. Other systematic and statistical errors have been combined in quadrature.) The acceptance used in calculating absolute cross sections was evaluated by comparing our measured yields for 4.8 GeV $p + Cu \rightarrow \pi^- + X$ with the cross section for this reaction obtained by Papp et al.[7]

By using information from all three detector stations and somewhat less restrictive geometry requirements we were able to make a sensitive search for antiprotons in a data sample of about six million events. To obtain an upper limit for $\bar{p}$ production we include, as a possible candidate, a single event found outside the K^- peak, and find (with 90% confidence level) $\bar{p}/\pi^- < 8 \times 10^{-7}$, and correspondingly, $d^2\sigma/dpd\Omega < 4$ nb/sr/GeV/c.

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 individual nucleon-nucleon collisions. The model assumes that nuclear collisions consist only of such collisions, but also includes an internal momentum distribution which accounts for subthreshold production in p-nucleus collisions. The model considers only first-encounter collisions and assumes that particle production is proportional to the available phase space with a transition matrix element that is independent of energy. This calculation is similar to those discussed in references 8 and 9. For the internal momentum distribution of nucleons within the nucleus we have adopted a double gaussian parametrization successfully employed by Geaga et al.[10] for fitting spectra of protons produced at 180° in various reactions. The width and relative magnitude of the term describing the higher momentum components is taken from this parametrization, and the width of the dominant term is taken from electron scattering data as reported by Moniz et al.[11] We find that this scheme closely reproduces the energy dependence of the data on subthreshold production in $p + Cu \rightarrow \bar{p}$ [8], see Fig. 3, and in $p + Be \rightarrow K^{-}$ [12].

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.

$$R \equiv \frac{\frac{1}{A_p A_T} \frac{d^2\sigma}{dp d\Omega}\left({}^{28}Si + {}^{28}Si \rightarrow K^{-}\ (2.1\ GeV/n)\right)}{\frac{1}{A_p A_T} \frac{d^2\sigma}{dp d\Omega}\left(p + {}^{63}Cu \rightarrow K^{-}\ (4.8\ GeV)\right)}$$

where A_p (A_T) is the mass number of the indicated projectile (target), and the yields are at 1 GeV/c and 0° in the laboratory. We find that $R_{meas} = 0.1 + 0.03$ (including the 17% systematic error referred to previously), which is 20 times larger than the calculated results $R_{calc} = 0.0045$. This discrepancy 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 degradation.

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[13] and measurements of $\pi N \to K^- x$ cross sections[14] results in a yield that is less than one tenth of the observed rate. (The calculated yield from this process in which the second step occurs on another nucleus is completely negligible.) Similar estimates of K^- production 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 discrepancy between the calculated and observed yields suggests that more complicated phenomena may be required in the production process. Fireball models which assume complete thermalization of the participating nucleons provide one natural framework in which subthreshold production 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. Calculations based on the work of K. A. Olive[15] give (for a fireball temperature of 110 MeV[16]) 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 sixty larger than our measured K^-/π^- ratio and a factor of eight above our $\bar{p}/\pi^-$ upper limit. a similar model[17] predicts K^+ yields in nuclear collisions approximately twenty times larger than those observed[14]. Preliminary calculations employing non-equilibrium thermodynamics[18] do appear to be in agreement with the observed yields.

Subthreshold production is also predicted by a number of models which require collective (but non-thermal) interaction among the participants. The collective tube model[19], 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. K. H. Muller[20] has suggested that the observed kaons may be produced by the decay of phi mesons which exist as virtual particles in the colliding nuclei and are radiated during the strong decceleration of the collision. Berenzovoi et al.[21] 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 KK 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 seems to be appreciably larger than that expected on the basis of simple nucleon nucleon interactions. Although several models which involve equilibration or multi-nucleon processes are rejected by our measurements, numerous other models or suggestions exist as possible explanations of the observed K^- yield. Further measurements are needed to determine the specific production mechanism.

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Figure Captions

Figure 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 Cerenkov (C) counters.

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

Figure 3. $p + {}^{63}Cu$ $\bar{p} + X$. anti-proton cross sections obtained by multiplying $\bar{P}/\pi^{-}$ ratios from Dorfan et al.[7] by pion cross sections from Papp.[21] Curve represents calculations employing a double gaussian parametrization for the internal nuclear momentum distribution.

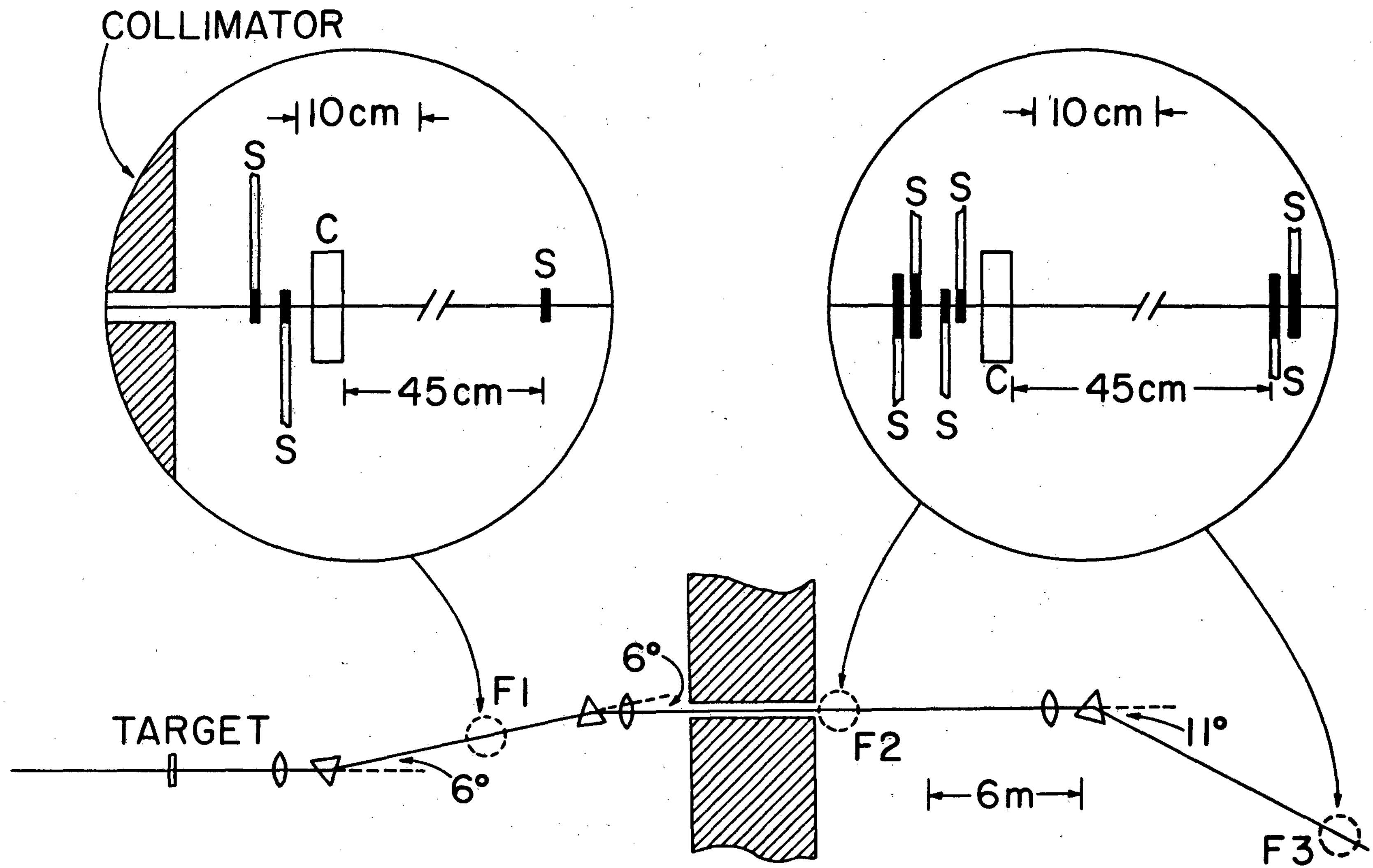
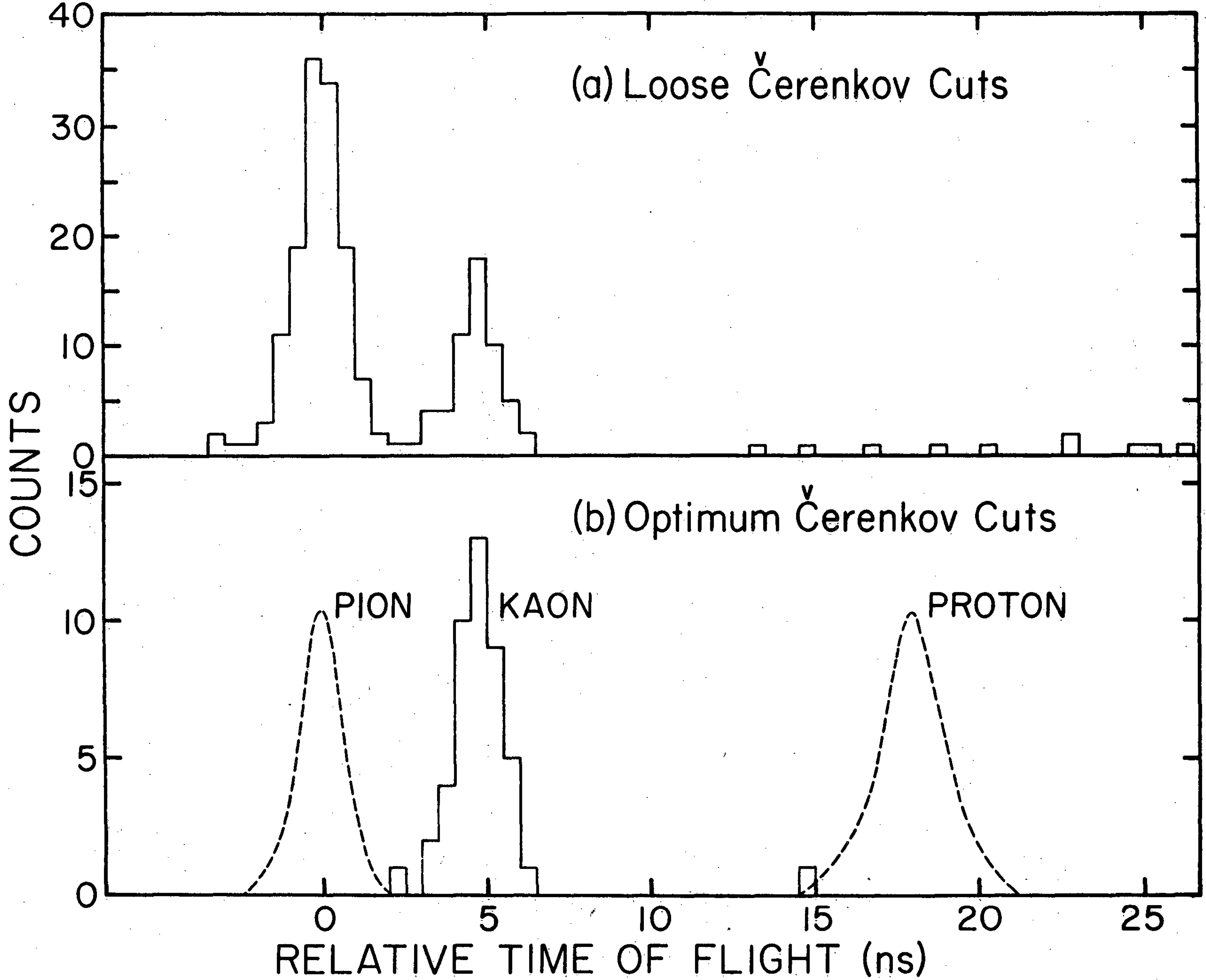
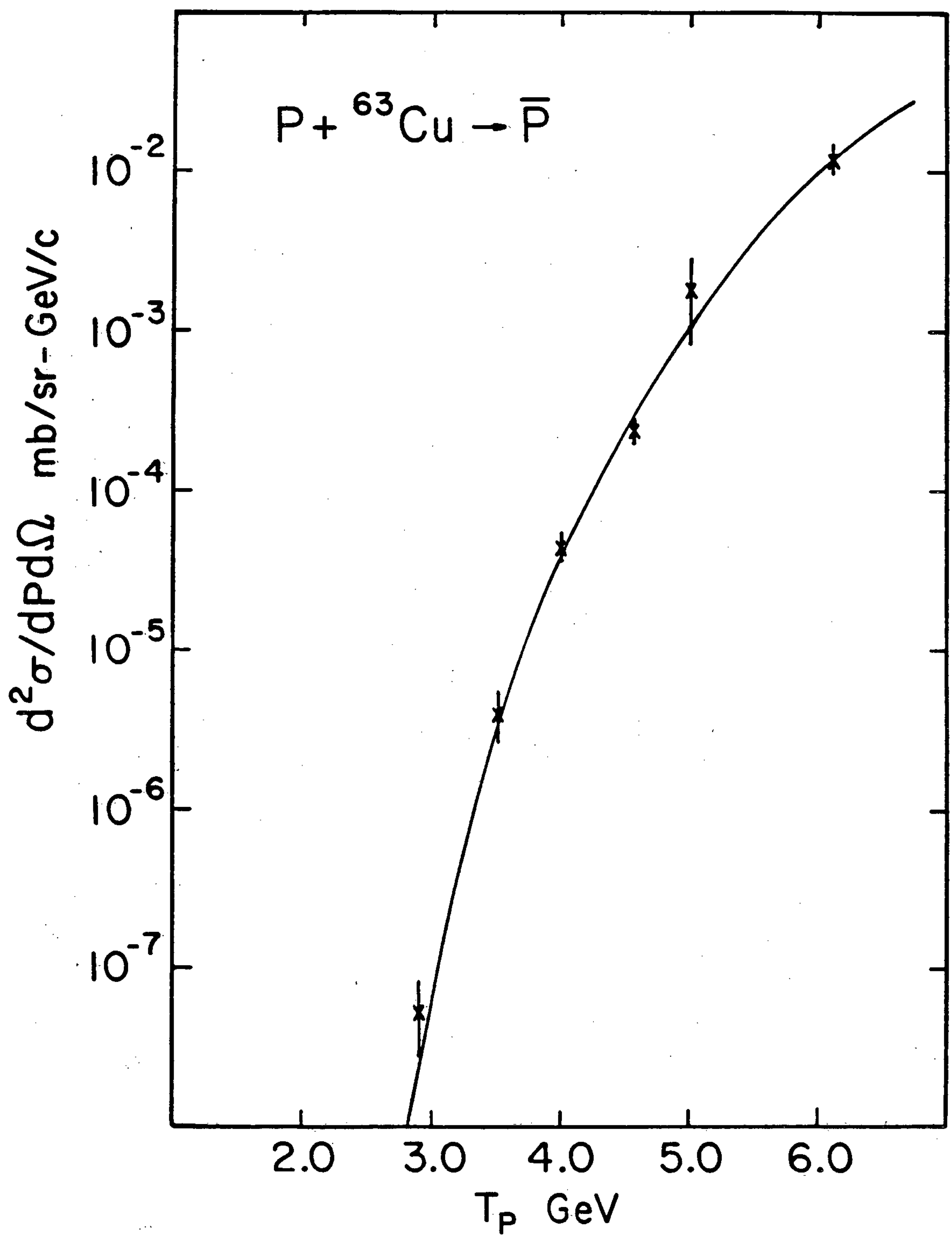

COLLIMATOR
10cm
S
S
C
S
45cm
10cm
S
S
S
S
C
S
S
45cm
TARGET
6°
F1
6°
F2
6m
11°
F3

Figure 1



(a) Loose Čerenkov Cuts
(b) Optimum Čerenkov Cuts
COUNTS
PION
KAON
PROTON
RELATIVE TIME OF FLIGHT (ns)
40
30
20
10
0
15
10
5
0
0
5
10
15
20
25

Figure 2



$P + {}^{63}Cu \rightarrow \bar{P}$
$d^2\sigma/dPd\Omega$ mb/sr- GeV/c
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
2.0
3.0
4.0
5.0
6.0
T_P GeV

Figure 3