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SUBTHRESHOLD ANTI-PROTON PRODUCTION IN ^{28}Si +^{28}Si COLLISIONS AT 2.1 GEV/NUCLEON

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ABSTRACT

We report on the first observation of subthreshold anti-proton production in nucleus-nucleus collisions. This measurement was made for the system ^{28}Si+^{28}Si at a bombarding energy of 2.1 GeV/nucleon ($KE_{c.m.}^{N-N} \sim 850$ MeV). A differential cross section $d^2\sigma/dPd\Omega$ of 80 ± 40 nb/sr-GeV/c was measured for $\overline{P}$ production at 1.9 GeV/c and 0^o. This result is three orders of magnitude larger than that predicted by a calculation incorporating internal motion of the nucleons in the colliding nuclei.

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Subthreshold production of particles in nucleus-nucleus collisions may probe collective effects that are not easily accessible through other techniques. Subthreshold pion production has been studied in a number of experiments[1,2,3,4], but is limited to low excitation energies and, except for collisions between very massive systems, the production process is strongly influenced by the effects of interactions in either the initial state ('Fermi momentum'), or the final state (production of bound nuclei), or both. The production of more massive particles permits the study of collectivity at higher excitation energies, and in regions of final state phase space where the above influences do not apply. The results of a recent survey of subthreshold K^- production[5] may contain indications of collective behavior, but since some of this yield can arise from strangeness exchange in intermediate states ($Y + \pi \rightarrow N + K^-$), a firm conclusion awaits more detailed analysis. Subthreshold production of anti-protons has no equivalent quantum number exchange, and as will be discussed later, internal nuclear momentum of the incident projectile and target nucleons cannot account for anti-proton production at the levels reported here.

We report here on the first observation of subthreshold anti-proton production in nuclear collisions. The experiment was performed at the Lawrence Berkeley Laboratory's BEVALAC in a beam line which was specifically designed for subthreshold K^- and $\overline{P}$ measurements. The spectrometer consisted of a secondary beam line with two magnetic bends, two sets of focusing elements, and detector stations at the two beam foci. A 25 degree bend beginning immediately downstream from the target separated the negative secondaries from the positively charged nuclear debris. A brass collimator at the first focus defined the secondary momentum acceptance to be $\Delta P/P \sim 1.5\%$. This collimator was built into a massive shielding enclosure that isolated the detector stations from the areas containing the target and primary beam. The first detector station contained two fast scintillation counters for time of flight (TOF) measurements - one directly downstream of the collimator and the second 2 meters further downstream, a focusing liquid Cerenkov counter ($\beta_{threshold} \sim 0.9\ c$) and two aerogel Cerenkov counters ($\beta_{threshold} \sim 0.98\ c$). The second detector station contained a third fast TOF scintillation counter, a focusing liquid Cerenkov counter, one Aerogel counter, several beam defining counters and a lead glass array at the end of the line for measuring total deposited energy. The total length of the lead glass array was about 2 interaction lengths. A CCD electronic readout of the first and third TOF counters sampled the pulse heights at 5 ns intervals to identify pile-up events. The total acceptance of the line was $\Delta\Omega \sim 5$ msr. The distance between the first and third TOF counter was 7.5 m (25 ns). A detailed description of the apparatus will be given elsewhere.[6]

The measurements reported here are for the reaction $^{28}Si + ^{28}Si$ at 2.1 GeV/nucleon ($KE^{N-N}_{c.m.} = 855$ MeV). The secondary line was tuned for 1.89 GeV/c negative particles produced at 0^o. The beam intensity (measured with a calibrated ion chamber) was $\sim 10^9$/spill, and the production target was 16 g/cm^2 thick, which is approximately one half of an interaction length for Si + Si. The total run lasted 21 hours. The main trigger consisted of a coincidence between several of the scintillation counters and a veto from at least two of the aerogel counters. A prescaled trigger containing no veto provided a large data sample for calibration and diagnostics. Time and pulse height information from all photomultipliers were digitized and recorded for each event. The offline analysis contained cuts to define clean events with no pile-up, and various Cerenkov cuts to identify the pion and kaon background. The TOF was corrected for shifts by monitoring the positions of the pion and kaon peaks.

Figure 1 shows spectra of the time of flight between the first TOF counter in detector station 1, and the TOF counter in detector station 2. Figure 1a is the TOF spectrum for events with a signal in all Cerenkov counters. The peak is identified as pions and has a σ of 110 ps. Figure 1b is the TOF for events with no signal in the aerogel counters. A clear K^- peak is seen. Figure 1c shows events with no signal in either the aerogel or liquid Cerenkov counters. Of the 1.94×10^7 pion pre-triggers accumulated, only five events, which we may designate as $\overline{C}$ events, survive these cuts. Figure 1a also shows where an anti-proton peak should be on the basis of an extrapolation from the pion and kaon peaks. The $\overline{C}$ events are distributed around the extrapolated anti-proton peak with a χ^2 of 4.9 for 5 degrees of freedom, but the probability that a grouping this narrow would arise from a flat distribution is less than 3%. For the $\overline{C}$ events, information from the intermediate TOF counter in detector station 1 is consistent with anti-proton TOF rather than that of pions or kaons, and the pulse height sampling of the CCD system shows clean signals with no indication of pile-up.

Figure 2 shows spectra of summed pulse heights from the lead glass blocks. (100 channels corresponds to 700 MeV equivalent electro-magnetic energy. The pedestal is at channel 1380.) Figure 2a shows the pulse height in the lead glass array for events identified as pions. Figure 2b shows the pulse height produced by the $\overline{C}$ events. On the basis of these summed pulse height distributions, the probability that the 5 $\overline{C}$ events belong to the pion distribution is less than 3% for a modified Wilcoxon rank sum statistic.[7] The fact that the pulse heights are larger for the $\overline{C}$ events than for pions also discounts the possibility that these events are H^- ions, which should deposit even less energy than pions. We thus identify the $\overline{C}$ events as anti-protons.

The $\overline{P}/\pi^-$ ratio is found to be 4.3×10^{-7} for secondaries at 1.9 GeV/c and 0^o for the reaction ^{28}Si + ^{28}Si at 2.1 GeV/nucleon. This corresponds to a differential cross section $d^2\sigma/dPd\Omega$ for anti-proton production of 80 ± 40 nb/sr-GeV/c. If we assume isotropic production in the center of mass system with an exponential slope with $E_0 \sim 100$ MeV, this would imply a total cross section of ~ 100 nb, or a total $\overline{P}/\pi^-$ ratio of $\sim 5 \times 10^{-8}$.

It is interesting to compare subthreshold anti-proton production in nuclear collisions, with that observed in p-A collisions. Figure 3 shows differential cross sections measured for $\overline{p}$ production in p-Cu collisions over a range of incident energies from near the p-p threshold at 6 GeV down to less than 3 GeV.[8] Also shown is the differential cross section for our $\overline{p}$ measurement in Si + Si collisions at 2.1 GeV/nucleon. (In the p-Cu measurements the anti-protons were nearly at rest in the N-N center of mass, while for the Si-Si data the anti-protons had a CM kinetic energy of 175 MeV.) Anti-proton production in Si + Si collisions at 2.1 GeV/nucleon is of the same magnitude as p + Cu at $\sim$ 4.3 GeV bombarding energy.

Reference 9 describes a calculation for subthreshold anti-proton production for p-A and A-A collisions. The calculation accounts for only first-chance N-N collisions and employs a double-Gaussian parameterization of the internal nuclear momentum, with the width of one Gaussian taken from electron scattering,[10] and the parameters for the second Gaussian extracted from data on backward proton production in p-A and A-A collisions.[11] The solid line in figure 3 shows the results of the calculation for p+Cu collisions. The excellence of the fit is an indication that down to the levels represented by the data on $p + Cu \rightarrow \overline{p} + X$, no high momentum components are needed beyond those represented by the double-Gaussian parameterization.

Figure 3 also shows the results of a calculation for $\overline{p}$ production in Si + Si (dashed line) where the internal nuclear momentum is included for both the projectile and target nucleons. This calculation is for an outgoing $\overline{p}$ laboratory momentum of 1.9 GeV/c. Our experimental result for anti-proton production in Si + Si collisions at 2.1 GeV/nucleon is 3 orders of magnitude larger than expected on the basis of these calculations which satisfactorily account for the effects of internal nuclear momentum in the p+Cu data. Note that these calculations do not fully include the effects of absorption of the $\overline{p}$ in the nuclear medium, which would make the discrepancy even larger.

Subthreshold particle production can occur in a sufficiently equilibrated system. Several models for thermal production of anti-protons have been advanced.[12,13] Ko and Ge have recently suggested[13] that subthreshold $\overline{p}$ production can occur through the reaction $\rho + \rho \rightarrow p + \overline{p}$. This model predicts $\overline{p}$ production at a level consistent with our observations. Ko and Ge, however, have assumed a thermal mechanism for ρ production, with a ρ abundance given by the equilibrium level

$$\frac{N_\rho}{N_\pi} = 3(\frac{m_\rho}{m_\pi})^{1.5} e^{-(m_\rho - m_\pi)/T}.$$

For T=100 MeV (as suggested by Ko and others for nuclear collisions at 2.1 GeV/nucleon), this equilibrium ratio is 7×10^{-2}. Recent preliminary data[14] on electron-pair production in Ca + Ca collisions at 2.1 GeV/nucleon have placed an upper limit on ρ_o production of 9 mb, which is equivalent to an upper limit on the ρ/π ratio of 5.7×10^{-3}. Clearly, the experimental upper limit for the ρ/π ratio is much lower than the equilibrium value. Not only does this raise serious questions about the model of Ko and Ge, it also suggests that ANY thermal model that requires significant populations in the higher Boltzmann levels is unlikely to contribute significantly to our observed yield.

In summary, we have observed subthreshold anti-proton production in ^{28}Si + ^{28}Si collisions at 2.1 GeV/nucleon. The observed $\overline{p}$ yield is about three orders of magnitude larger than predicted by a theoretical model which includes the effects of internal nuclear momentum of the colliding nucleons. It has been brought to our attention that subthreshold anti-proton production has been recently observed at JINR for C+Cu at 3.65 GeV/nucleon.[15] Although this measurement is at a bombarding energy significantly larger than that reported here, a comparison at different bombarding energies should shed light on the collective mechanism responsible for subthreshold anti-proton production in relativistic nuclear collisions.

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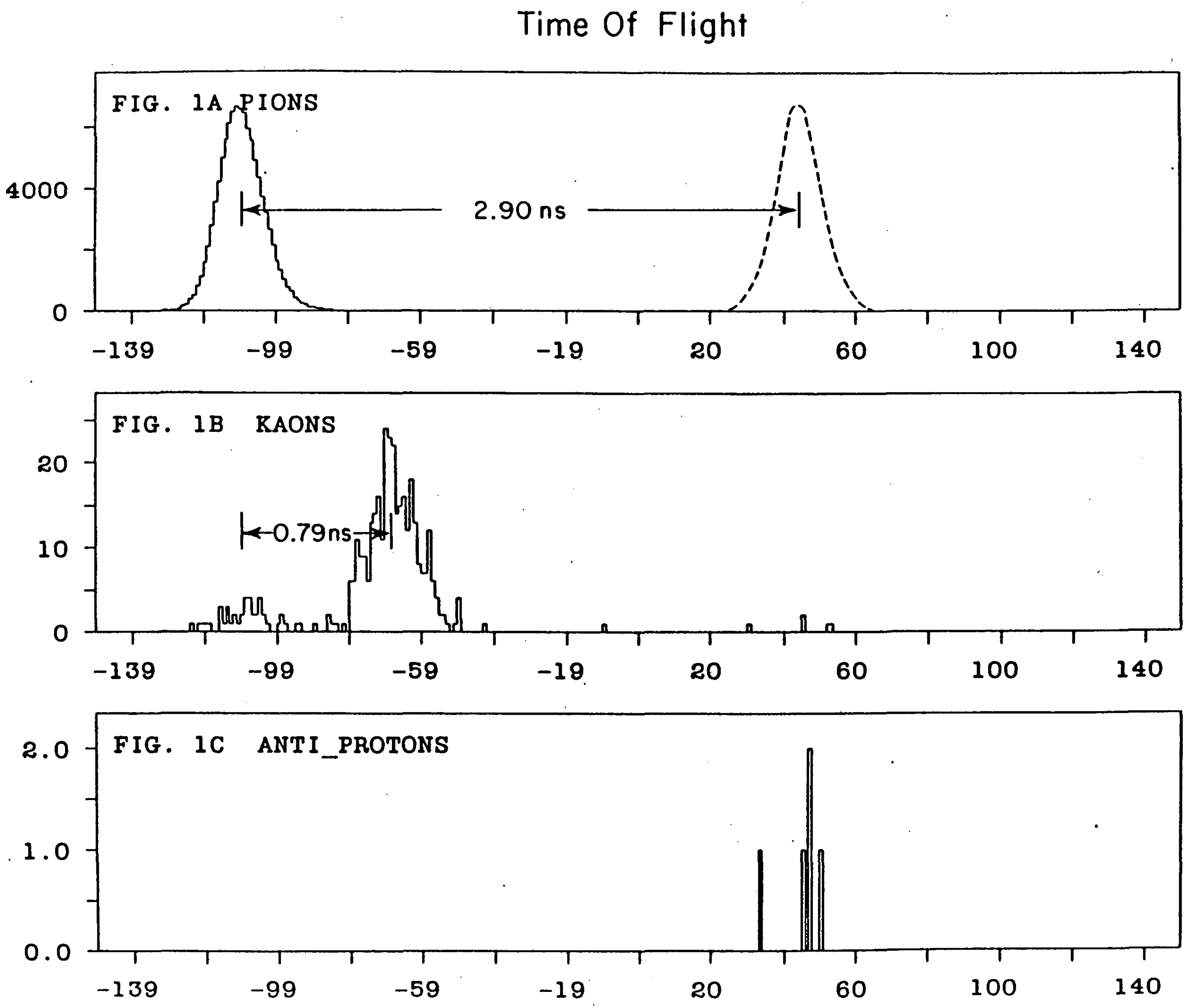
FIGURE CAPTIONS

Figure 1. TOF distribution between 1^{st} detection area and 2^{nd} detection area ($\sim$ 25 ft.). Fig. 1a, TOF for events which trigger aerogel Cerenkov counters. Fig. 1b, TOF for events with no aerogel signal. Fig. 1c, TOF for events with no aerogel or liquid Cerenkov signal.

Figure 2. Lead glass response (summed). Fig. 2a, lead glass response for events identified as pions. Fig. 2b, lead glass response for 5 events identified as anti-protons.

Figure 3. Subthreshold anti-proton production in p+Cu collisions (symbol $\times$), and a comparison with $\overline{p}$ production in Si+Si collisions (symbol S). Solid line is calculation for $p+Cu \rightarrow \overline{p}+X$ incorporating a double Gaussian distribution for the internal nuclear momentum (ref. 14). Dotted line is same calculation for $Si + Si \rightarrow \overline{p} + X$.



Time Of Flight
FIG. 1A PIONS
4000
0
2.90 ns
-139
-99
-59
-19
20
60
100
140
FIG. 1B KAONS
20
10
0
0.79ns
FIG. 1C ANTI_PROTONS
2.0
1.0
0.0

Figure 1

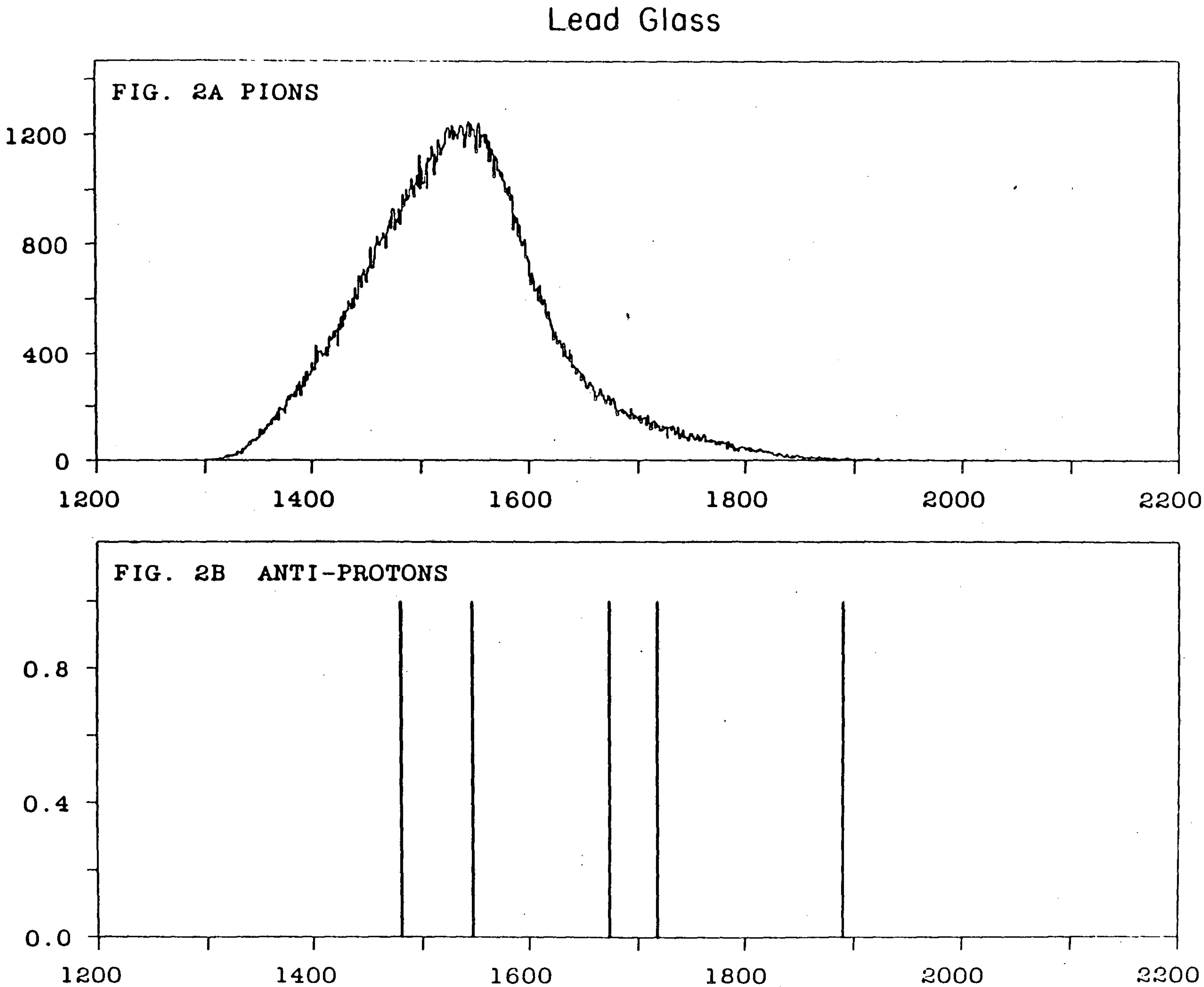
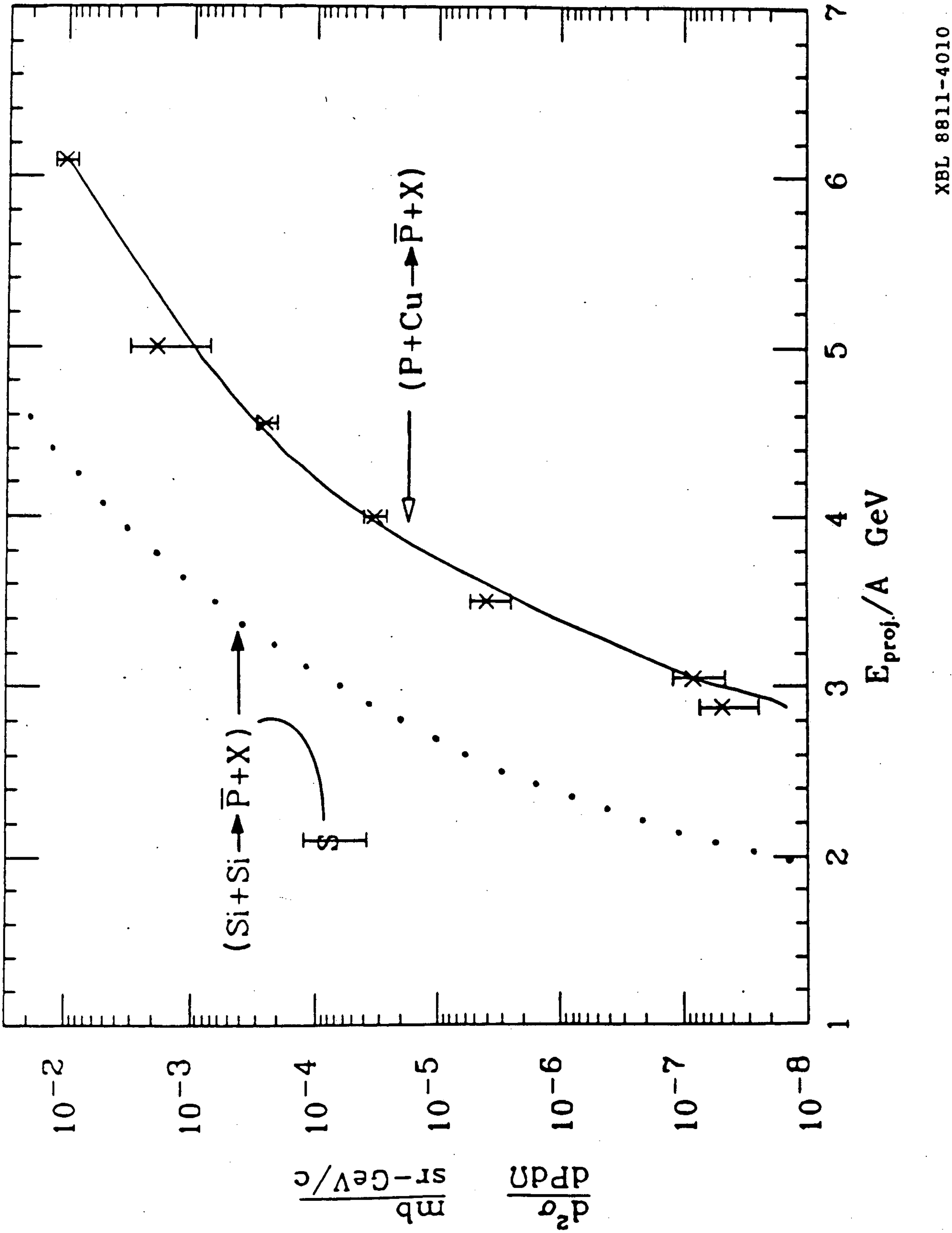

Lead Glass
FIG. 2A PIONS
1200
800
400
0
1200
1400
1600
1800
2000
2200
FIG. 2B ANTI-PROTONS
0.8
0.4
0.0
1200
1400
1600
1800
2000
2200

Figure 2



(P+Cu→P̄+X)
(Si+Si→P̄+X)
$E_{proj.}/A$ GeV
1
2
3
4
5
6
7
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$\frac{d^2\sigma}{dPd\Omega}$ $\frac{mb}{sr-GeV/c}$
XBL 8811-4010

Figure 3