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Production of Antiprotons by High Energy Photons

by

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Abstract

Experimental evidence is presented for the photoproduction of antiprotons on nitrogen and hydrogen by photons of energy 4.1 - 6.2 GeV. Yields and $\bar{p}/\pi$ ratios are given and compared to a simple one-nucleon-exchange model.

The maximum bremsstrahlung energy of 6 GeV available at the Cambridge Electron Accelerator (CEA) and at the Deutsches Elektronen-Synchrotron (DESY) is sufficiently high to permit the production of antibaryons by photons. The kinematical threshold for antiproton production on a nucleon at rest is four nucleon masses M and may be lowered to about 3.2 M by using the Fermi motion of nucleons in complex nuclei, assuming a kinetic energy of T = 25 MeV.

In a recent photoproduction experiment at CEA, Gettner et.al.[1] observed a peak in the time-of-flight spectrum of negatively charged particles and interpreted it as probably due to antiproton production. The existence of this process could not be established with certainty, however, because of limited statistics and of an unexplained shift of this peak relative to the proton peak obtained on reversing the polarity of the spectrometer.

We are presenting here evidence for the production of antiprotons by photons of energy 4.1 - 6.2 GeV incident on a liquid nitrogen target. The antiprotons were observed at a laboratory angle of 8° in the momentum range 1.7 - 2.6 GeV/c using a magnetic spectrometer for momentum analysis of particles and a threshold Cerenkov counter to suppress the large pion background. Final identification of antiprotons was done by a time-of-flight method.

In addition, we have measured antiproton production on hydrogen at 6.2 GeV photon energy, 8° laboratory angle, and 2 GeV/c momentum of the antiproton.

The layout of the apparatus is shown in Figure 1. The bremsstrahlung beam was defined by two lead collimators and cleaned by two sweeping magnets before impinging on the 7 cm diameter cylindrical target cell. Its intensity was monitored by a gas-filled quantameter of the Wilson type[2].

Charged particles emerging from the target at $(8.0 \pm 0.6)^{\circ}$ were momentum-analyzed in a magnetic spectrometer consisting of two synchrotron-type magnets and two quadrupoles for beam shaping and two bending magnets for momentum analysis. The spectrometer accepted a momentum band of $\pm$ 2.8 %. The total acceptance was calculated by a Monte Carlo method taking into account the effective target size, Coulomb scattering, and counter sizes, yielding $\int d\Omega dp/p = 0.014$ mster. The error in the acceptance is estimated to be $\pm$ 5 %.

Behind the spectrometer the particle beam traversed a series of scintillation counters S1...S5. Counters S2 and S3 were placed directly in front of and behind a 3.5 m long gas threshold Cerenkov counter[3] to guarantee 100 % geometrical efficiency for pion rejection by the Cerenkov counter. The gas filling of this counter was ethylene, its pressure was set at 4.2 atm, i.e. below the threshold for counting K mesons. Its efficiency for counting pions of 2 GeV/c was measured as $\approx$ 99 %.

A fast coincidence (2345) with 5 nsec resolution (FWHM), timed for protons and having a rejection ratio of $\geq$ 5:1 against pions of 2 GeV/c served as a master trigger for the electronics. Two coincidences (2345$\bar{C}$) and (2345C) routed the time-of-flight signals to two memory subgroups of a pulse height analyzer. The flight time of particles was measured between counters S1 and S5 having a separation of s = 16.85 m (15.55 m for some early runs), using a system of the type described by Ward et.al.[4] to improve the resolution by compensating for the large counter sizes. The time resolution of this system was 1.3 nsec FWHM.

Our method of gathering evidence for the photoproduction of antiprotons is similar to that used by Dorfan et.al.[5]. Time-of-flight spectra of positive particles at 2.0 GeV/c momentum established the position of the proton and pion peaks, their resolution, and the pulse height analyzer calibration of 0.25 nsec/channel. The proper functioning of the electronics was further checked by observing the shift in the position of the proton peak with momentum at 1.7, 2.3, and 2.6 GeV/c, which agreed to within 0.2 nsec with the calculated values.

Our evidence for antiproton production on nitrogen is contained in the time-of-flight spectra for negative particles at 1.7, 2.0, 2.3, and 2.6 GeV/c shown in Figures 2 and 3, and in the excitation curve of Figure 4. The evidence is based on the following observations:

(1) At 2.0 GeV/c and negative polarity we find a well-separated peak at the same position where the proton peak occurs in the corresponding positive-polarity run, see Figure 2. The agreement in peak position is better than 0.2 nsec which corresponds to a mass difference $\Delta M = p\gamma(c/s)\Delta t$ of less than 18 MeV. This is consistent with pulse height analyzer drift. Time drift due to magnet instabilities $\Delta t = -(sM^2/Epc)\Delta p/p$ is negligible in comparison.

(2) The shift of the negative polarity peak with momentum agrees to within 0.2 nsec with the corresponding proton peak shift, both observed and calculated, see Figure 3.

(3) Independent evidence is furnished by the excitation curve of Figure 4. With the spectrometer setting fixed at 8° and

2 GeV/c, the maximum bremsstrahlung energy was varied between 4.1 and 6.2 GeV. Noting that the threshold for observing antiprotons at this setting is 4.16 and 3.58 GeV for Fermi energies of 0 and 25 MeV, respectively, we conclude that the threshold behavior of the excitation curve is consistent with antiproton production.

Our results for antiproton yields and for $\bar{p}/\pi$ ratios are summarized in Tables 1 and 2.

Several corrections have been applied to the data. Among these, the corrections for $\bar{p}$ absorption on complex nuclei are difficult to calculate since very little published data exist. The empirical formula given by Williams[6] for the inelastic cross sections of protons and pions on nuclei is not readily applicable to the antiproton case. Inelastic $\bar{p}$ cross sections on nuclei at 1.03 GeV/c have been measured by Segré et.al.[7] and yield an approximate $A^{2/3}$-dependence. Using this dependence and the total $\bar{p}p$ cross section of Amaldi et.al.[8] we find that the absorption correction increases our yields at 2 GeV/c by (50 ± 15) %. The 15 % uncertainty in this correction is an estimate which reflects our lack of knowledge of the $\bar{p}$-nuclei cross section. The absorption correction includes diffraction-scattering of antiprotons since they have only a very small chance of going through the spectrometer.

We have considered the possibility that the antiprotons are not photoproduced directly, but are created via a two-stage process, viz. photoproduction of pions which subsequently produce antiprotons. Assuming such a two-stage process, we would expect the antiproton yield to increase with the square of the target thickness. Thus, we may test this hypothesis by varying the target thickness. We have done this by using nitrogen and hydrogen, respectively, in the same target cell. This is equivalent to varying the target thickness for the pion production stage since according to Blumenthal et.al.[9] Drell pion photoproduction depends on atomic number A as $A^{1.0 \pm 0.1}$. Assuming the same A-dependence for $\bar{p}$-production by pions we may calculate R, the expected ratio of the number of antiprotons produced from nitrogen and hydrogen, respectively. We calculate this ratio R = 130. Assuming $\bar{p}$-production by pions to be a nuclear surface effect instead, we have to multiply this figure by $A^{-1/3}$, obtaining R = 54. We have measured, however, R_{exp} = 5.7. With both assumptions, then, there is a large discrepancy between calculation and experiment which indicates that antiproton production through intermediate pions must be small.

We can check this conclusion independently by estimating directly the number of antiprotons that could be produced by Drell pions photoproduced in the target. Using Blumenthal's results we estimate that at 6 GeV photon energy the total number of pions effective for $\bar{p}$-production is $\approx 3 \times 10^{-6}/Q_{eff}$. Assuming a total cross section of 10 μb/nucleon for antiproton production by pions on nucleons[10] and that these antiprotons are produced uniformly within a laboratory solid angle of 1 sterad, we calculate that fewer than 10^{-3} of the observed antiprotons could have been produced via Drell pions. The estimates used in this calculation are probably conservative by about a factor of 10.

Speculating on possible mechanisms for antinucleon photoproduction, one is inclined to try an approach similar to the peripheral model of Drell[11], used with some success in pion photoproduction. The original Drell formula[12] cannot be applied directly to our case since it was derived for the high energy limit where the antinucleon and photon energies are much greater than the nucleon mass. A straight-forward evaluation after Drell of the one-nucleon-exchange diagram in which the high-energy-limit approximation is not made has been given by Kohaupt[13]. The calculation predicts yields which are two orders-of-magnitude larger than our measured values. This disagreement is not too surprising since one has neglected: (a) the reduction of the final state amplitude due to absorption, and (b) damping due to form factors both for the photon vertex and for the nucleon propagator when the nucleon is far off the mass shell.[14] It is also to be remembered that the one-nucleon-exchange diagram need not necessarily dominate the antinucleon production process.

We wish to acknowledge the continued interest and help received from Professors W. Jentschke and P. Stähelin. Thanks are also due to Professor H. Joos for stimulating discussions and to Dr. Kohaupt for deriving the modified Drell formula. Finally, we thank Mr. Kumpfert and the synchrotron operating crew for their efforts, which made this experiment possible.

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Kohaupt's result for antiproton production on a nucleus X can be written as

$$\frac{d^2\sigma}{d\Omega dE} = \frac{\alpha}{8\pi^2} \times \frac{\beta E((k-E)^2-M^2)^{1/2}}{k^3} \times \frac{r}{(1-\beta\cos\theta)^2} \times \sigma_{p+X,tot}$$

with

$$\begin{aligned} E^2 x r = {} & 2(a+\lambda)^2\left((k-E)E + M^2 - (\hat{k}\cdot\vec{p})(\hat{k}\cdot\vec{q}) \right) \\ & + \frac{\lambda^2}{4M^2}\left(\left((k-E)E - (\vec{q}\cdot\vec{p})\right)\left(\vec{Q}^2 - (\vec{Q}\cdot\hat{k})^2 \right) + M^2(\vec{Q}\cdot\hat{k})^2 \right) \\ & + \lambda(a+\lambda)\left(\vec{Q}^2 - (\vec{Q}\cdot\hat{k})^2 \right) \end{aligned}$$

where

$E, \vec{p}, \beta, \theta$ are total energy, momentum, velocity, and angle, respectively, of the antiproton

k the γ-energy

$\hat{k}$ a unit vector in the direction of the γ-quantum

$\vec{q}, a, \lambda$ momentum, charge, and anomalous magnetic moment, respectively, of the exchanged proton

$\vec{Q} = \vec{q}-\vec{p}$.

From this formula we calculate a yield of $d^2\sigma/d\Omega dp$ = 450 μb/srGeV/c per nitrogen nucleus at 6 GeV, assuming $\sigma_{tot}(N)$ = 250 mb. Our experimental value, which can be calculated from the excitation curve, is 3.5 μb/srGeV/c.

[14] S.D. Drell in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Vol. I, Hamburg, June 1965, p.79.

Figure 1

Layout of the Apparatus

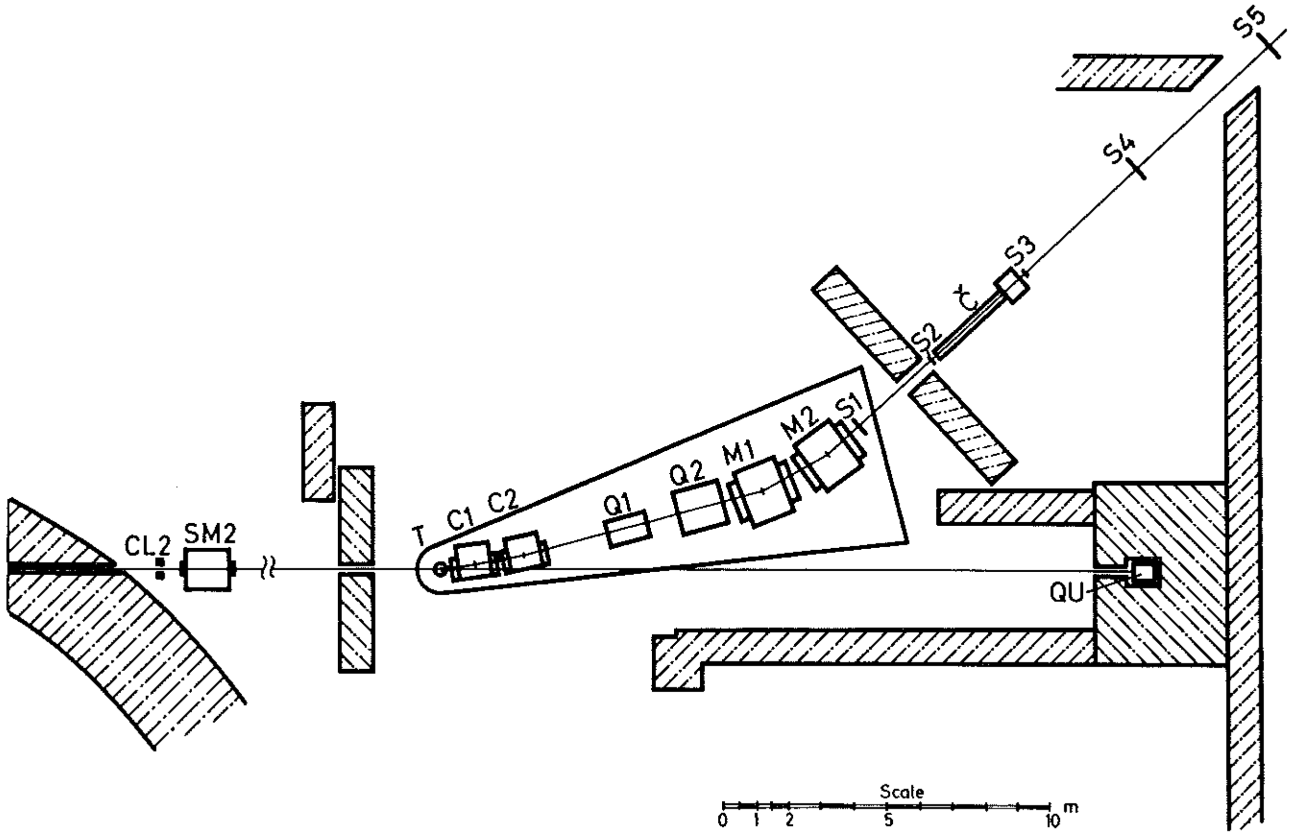

Figure 2

Top: Time-of-flight spectra of 2.0 GeV/c negatively charged particles with signature $(2345\bar{C})$ (heavy lines, left scale) and (2345C) (thin lines, right scale). The left peak is due to antiprotons. The contribution to the right-hand peak of K mesons is evident in the displacement of this peak from the π peak position. No $K^-/\bar{p}$ ratio can be extracted from this graph, however, since kaons are suppressed by the timing of (2345).

Bottom: Calibration spectra for positive polarity, $(2345\bar{C})$ left, (2345C) right.

k_{max} for all spectra: 6.2 GeV, target: liquid nitrogen.

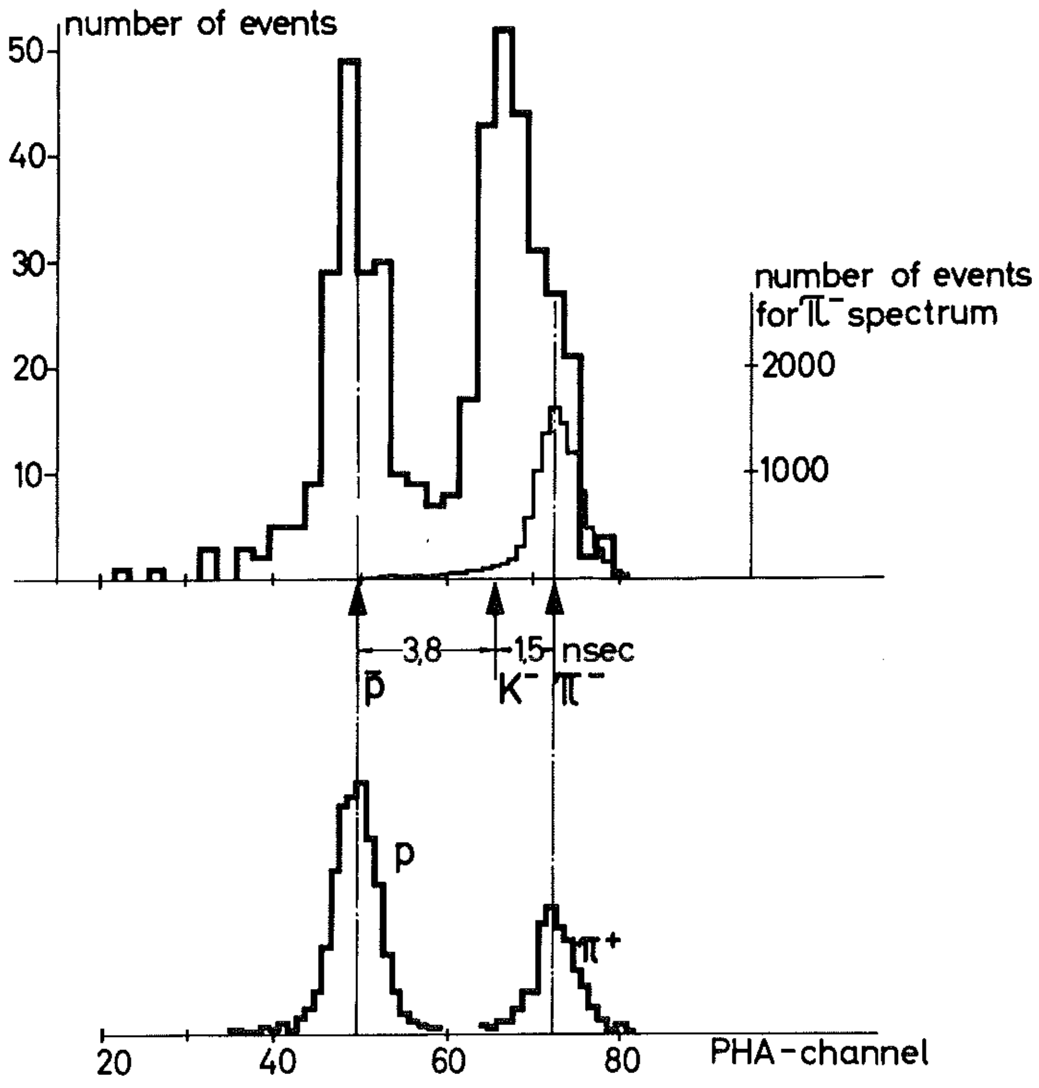

Figure 3

Time-of-flight spectra of negatively charged particles with signature (2345$\bar{C}$) at various momenta. Top: 1.7 GeV/c; the suppression of K^- and π^- due to the timing of (2345) is almost complete. Second from top: 2.0 GeV/c; the timing of (2345) is somewhat different from that of Figure 2, causing both the channel number of the $\bar{p}$ peak and the suppression of K's and π's to be different. The small arrows indicate the proton peak position in the corresponding positive-polarity runs.

k_{max} for all spectra: 6.2 GeV, target: liquid nitrogen.

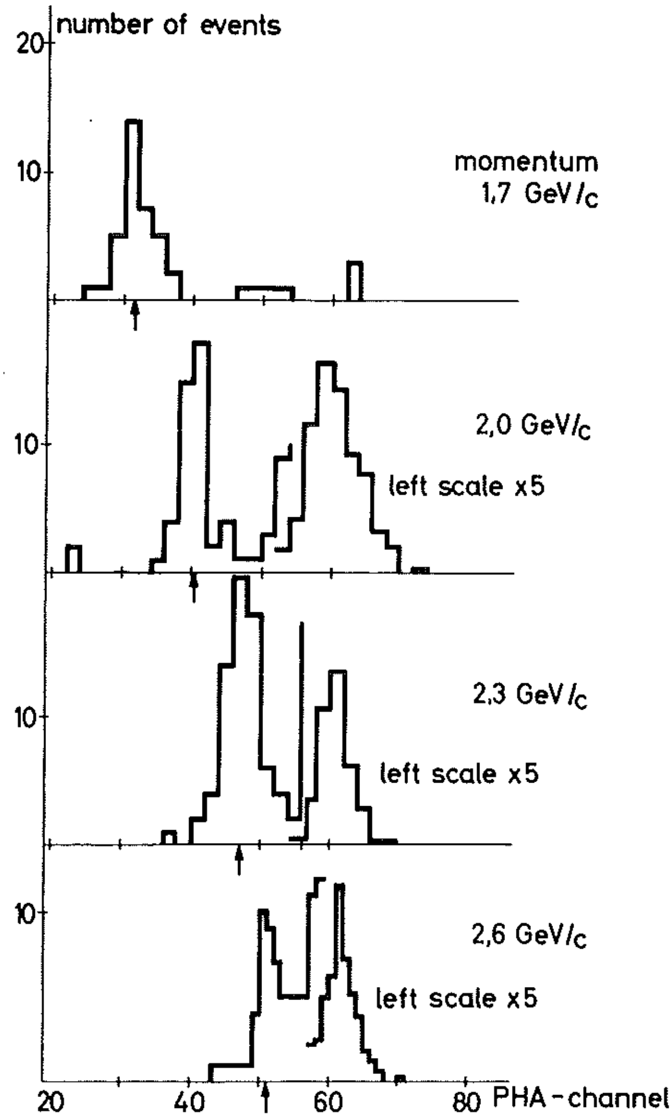

Figure 4

Excitation curve for antiproton yield per effective quantum from nitrogen at 8^{o} laboratory angle and at 2.0 GeV/c momentum for the $\bar{p}$. The point at 3.0 GeV was taken as a consistency check of the electronics and yielded no event. At 4.1 GeV we found 3 events, indicating antiproton production via nuclear motion, see text.

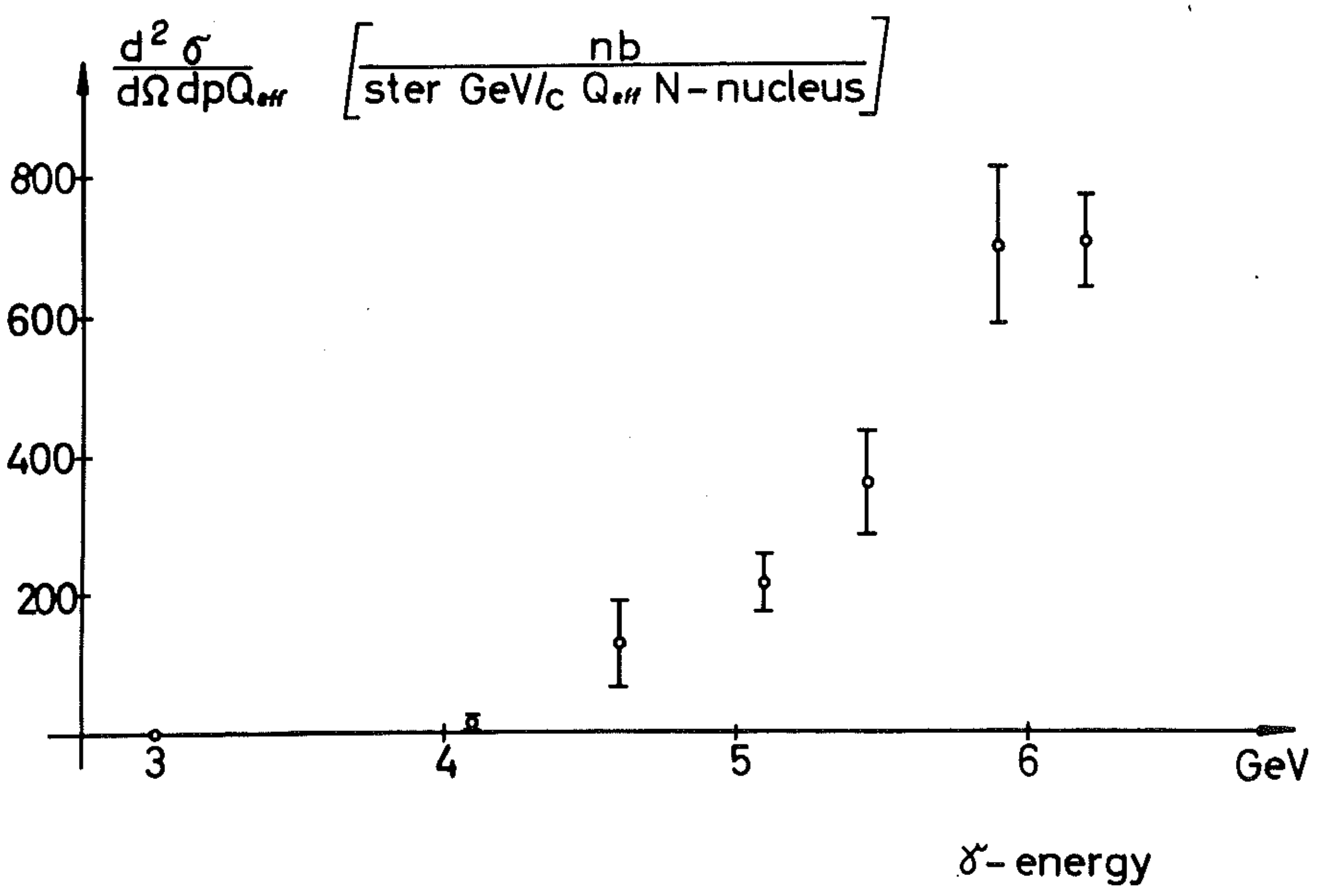

Table 1

I) Antiproton yield from liquid nitrogen at $\theta_{lab,\bar{p}} = 8^o$, $p_{\bar{p}} = 2.0$ GeV/c, as a function of photon energy.

II) Antiproton yield from liquid hydrogen at 8° and 2.0 GeV/c.

III) Hydrogen-nitrogen ratio of yields at 6.2 GeV, 8° and 2.0 GeV/c.

The number of antiprotons was found without using any fitting procedure by counting the number of events under the peak. The errors indicated are due to statistics and $\bar{p}$ peak cut-off; in addition, there is an estimated systematic error of ± 15 % due to the uncertainties in the acceptance, the absorption correction, and the beam monitoring. All results are corrected for Coulomb scattering and nuclear absorption of antiprotons and pions, and for pion decay.

	k_{max} (GeV)	number of $\bar{p}$'s	number of eff.quanta	$\frac{d^2\sigma}{d\Omega dpQ_{eff}\text{nucleus}}\left[\frac{\text{nbarn}}{\text{ster(GeV/c)Qn}}\right]$	$\frac{\bar{p}}{\pi^-}$
I)	6.2	178±16	5.90×10^{13}	700 ± 63	5.25×10^{-4}
	5.9	71±11	2.38×10^{13}	695 ± 108	
	5.45	43± 9	2.82×10^{13}	356 ± 74	3.5×10^{-4}
	5.1	44± 9	4.78×10^{13}	212 ± 43	
	4.6	8± 4	1.52×10^{13}	122 ± 61	
	4.1	3± 2	4.23×10^{13}	17 ± 11	2.3×10^{-5}
	3.0	0	0.81×10^{13}	0	
II)	6.2	58± 9	1.10×10^{14}	96 ± 15	1.06×10^{-3}
III)	$d^2\sigma(H) : d^2\sigma(N) = 1 : (7.3 \pm 1.0)$				

Table 2

Momentum spectrum of antiproton yields from liquid nitrogen at 6.2 GeV and 8°. The same remarks apply as in Table 1.

$p_{\bar{p}}$ (GeV/c)	number of $\bar{p}$'s	number of eff.quanta	$\frac{d^2\sigma}{d\Omega dpQ_{eff}\text{nucleus}}\left[\frac{\text{nbarn}}{\text{sterGeV/cQn}}\right]$	$\frac{\bar{p}}{\pi^-}$
1.7	35±10	0.56x10^{13}	1750 ± 500	---
2.0	46± 9	1.69x10^{13}	636 ± 125	5.25x10^{-4}
2.3	70±11	1.68x10^{13}	830 ± 130	7.5 x10^{-4}
2.6	45±12	1.68x10^{13}	455 ± 120	5.3 x10^{-4}