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CROSS SECTIONS OF ANTIPROTONS
IN HYDROGEN, BERYLLIUM, CARBON, AND LEAD

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I. INTRODUCTION

Previous experiments have shown that the antiproton interacts strongly with matter. At 500 Mev for lead glass, cooper, and beryllium, and at lower energies for photographic emulsions, the absorption cross section is significantly greater than geometric. The purpose of the experiment reported here was to extend to other elements the measurements on the interaction of antiprotons and, in particular, to measure as a function of energy the total proton-antiproton cross section, which is of central importance to the understanding of the nucleon-antinucleon interaction.

In order to fit the experimental program into a feasible time schedule, considerable effort was spent in the development of a usable antiproton beam of high intensity. The use of this beam in the production and identification of antineutrons has been described in an earlier report.

The magnetic channel and the basic electronics are described in Sections II and III respectively, while operation of the antiproton identification scheme is included in Section IV. The attenuation experiment in hydrogen is described in Section V, and the measurements on beryllium, carbon, and lead in Section VI.

II. MAGNETIC BEAM CHANNEL

Antiprotons were produced in a 5-inch-long beryllium target in the internal beam of the Bevatron (Fig. 1). From this point at 5° from the end of the quadrant, negative particles produced in the forward direction were deflected by the magnetic field toward a thin [1/16-inch] section of the vacuum-tank wall.

On leave from Brookhaven National Laboratory.
The external beam channel (Fig. 1) was designed to carry a beam of considerable momentum width over the required time-of-flight path. Five quadrupole lenses of nominally 4-inch aperture were employed; each lens was composed of two quadrupoles 8 inches long and one 16 inches long. The first lens, \( Q_1 \), was placed as close as feasible (130 inches) to the internal target so as to obtain the maximum solid angle of acceptance. To attain sufficient focusing power from available units and to allow some choice in magnification, the three quadrupoles in \( Q_1 \) were arranged to function as a two-element lens. The two 8-inch units were adjacent with their fields aiding and in a direction opposite to that in the 16-inch quadrupole that followed; a 7.25-inch interval between these quadrupoles was the minimum allowed by the water and electrical connections. \( Q_1 \) formed an image of the beryllium target at the entrance to \( Q_2 \) and effected a transition into the repeating pattern of lenses that followed. Each of the four lenses after \( Q_1 \) was adjusted to focus particles emerging from the lens preceding it into the aperture of the succeeding lens. For particles at the center of the momentum interval accepted, lenses \( Q_2 \) and \( Q_4 \) were located at the target image points, and in this sense bear some analogy to field lenses in an optical system. Such an array of lenses uniformly spaced at twice the focal length presents a good aperture to particles from an extended source and over a broad momentum range; it is a feature of this system that the aperture remains large when the channel is lengthened by the addition of lenses. The broad admittance of this beam channel not only permitted a large flux of particles, but also reduced beam loss from scattering in the vacuum-tank wall and in the scintillators. Our lenses \( Q_2 \) through \( Q_5 \) were each symmetric arrangements of quadrupoles with the 16-inch unit in the center separated from the 8-inch units by 10.5-inch intervals. The series of magnetic lenses carried negative particles a distance of about 100 feet from the target. At 1.4 Bev/c momentum, the lenses after \( Q_1 \) operated with gradients of about 3600 gauss/inch; \( Q_4 \) had about 2800 gauss/inch, and the lenses were spaced with 251 inches between centers.

The dispersion of the magnetic field in the Bevatron produced a horizontal extension of the target image at \( Q_2 \). The magnification of \( Q_1 \) and deflection in the first analyzer magnet, \( A_1 \), increased this effect and allowed adjustment of the momentum interval entering the aperture of \( Q_2 \). The analyzer magnets also served to reject positive particles that scattered into or were produced along the beam path.
In addition, three monitors were provided. A scintillation telescope \( M_1 \), looking directly at the internal target, monitored the beam spill-out. A coincidence circuit \( M_2 \), connected to alternate outputs of Counters C and E and timed to count \( p \) mesons, monitored the channel flux; and the signal from a beam induction electrode in the Bevatron was integrated to provide a record of the total circulating beam.

The structure of the Bevatron circulating beam during acceleration has pronounced rf modulation. To reduce the peak counting rate encountered by our time-of-flight scintillators, the following beam spill-out technique was employed. The circulating proton beam was steered into a thin aluminum foil (0.0003 inch) at the outer radius. The energy loss sustained in repeated passage through this foil caused the protons to become phase-unstable and to spiral inward in the increasing magnetic field of the Bevatron. In the several milli-seconds required to spiral into the beryllium target all phase coherence was lost, and a beam spill-out of uniform intensity was obtained. By control of the rate at which the initial beam was driven into the foil, the length of the spill-out could be adjusted. In this experiment, a 100-millisecond spill was used, corresponding to an energy range of the internal beam of from 5.8 to 6.2 Bev.

IV. IDENTIFICATION OF ANTI-PROTONS

The intervals AC, CE, BD, and DF between counters were each long enough to reject single \( p \) mesons by a large factor (\( \approx 10^3 \)) when the counters were timed for antiprotons (\( \beta \approx 0.625 \) to 0.83). Similarly, twofold accidentals were rejected because, for example, two mesons that simulated an antiproton in the interval AC could not simultaneously do so in the interval CE. The use of two such coincidence circuits serves a double purpose. First, the probability that an accidental coincidence occurs in two slightly detuned independent circuits is the product of the probabilities for each. Thus the rejection of mesons is improved. In addition, some rejection against threefold accidentals can be obtained by staggering the intervals so that we have AC > CE while BD < DF. Separation of the antiprotons was, of course, most difficult at the highest velocity employed (\( \beta \approx 0.83 \)). The lengths of the cables connecting each counter with the coincidence circuit determined the velocity to which the electronic system was sensitive, and therefore defined the mass of particles selected. Figure 3 shows the number of coincidences obtained at 1.4 Bev/c as the relative
hydrogen cylinder was supported in a vacuum (less than $10^{-5}$ mm Hg) by radial

cables, and surrounded by heat shields inside a liquid nitrogen jacket. The
liquid nitrogen was insulated by styrofoam and Santopan.

The target was made of 310 stainless steel, ultrasonic welded. (See
UCRL Engineering Note 7307-01-M16.) The target can be disassembled by
grinding the cylindrical welds. Each of the end windows is of spun stainless
steel 0.020 inch thick. The four steel windows through which the beam passed
totaled about 2 g/cm². The hydrogen container was tested at a hydrostatic
pressure of 130 lbf per in². During operation the target was vented to the
roof of the building. The target used approximately 1.5 liters of liquid hydrogen
per hour provided the reservoir was only partially filled. The hydrogen could
be put in or removed in about 15 minutes. At each energy several runs with
and without hydrogen were made.

The geometry for $L$ (Fig. 5) was chosen so that the half angle subtended by $L$ at the target was as small as possible consistent with negligibility
of uncertainty due to multiple Coulomb scattering and the natural spread of
the beam from the selecting system. In this way the uncertainties due to for-
ward scattering and annihilation secondaries were minimised.

Figure 6 shows the experimental results obtained at each energy.
Values for the transmission of the hydrogen target, as obtained from the scalers
and from the oscilloscope, are in good agreement. Cross sections in the figure
are those obtained from the oscilloscope, which was less sensitive than the
scalers' readings to fluctuations in the pulse height from $L$. Uncertainties indi-
cated are statistical only.

Determination of the total cross section for the interaction of anti-
protons with protons requires a correction for the finite solid angle subtended
by Counter L at the target. The value of this correction may be estimated from
the formula relating the imaginary part of the forward scattering amplitude,
$I_0$, to the total cross section $\sigma_T$:

$$ I_0 = \frac{\sigma_T}{4\pi} $$

where $\lambda$ is the wave length of the incident antiproton. The magnitude of the

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scattering. In this case, however, the correction for forward nuclear scattering is much larger. The correction has been made with the assumption that the forward scattering is a diffraction effect resulting from absorption over a uniform partially transparent disk of radius $3 \times 10^{-13}$ cm, but the amount of this correction is found to be insensitive to the disk radius assumed. Uncorrected and corrected values for the cross section are given. The uncertainty expressed is statistical only. The energies given in the table correspond to the antiproton kinetic energies at the center of the Be target and are uncertain by ± 5%.

Table II

<table>
<thead>
<tr>
<th>Target thickness</th>
<th>T_p (Mev)</th>
<th>$\theta_{1/2}$ (degrees)</th>
<th>$\sigma_{obs}$ (mb)</th>
<th>$\sigma_{cor}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g/cm²)</td>
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<td></td>
</tr>
<tr>
<td>27.9</td>
<td>500</td>
<td>2.57</td>
<td>460</td>
<td>484 ± 60</td>
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<td>24.4</td>
<td>700</td>
<td>3.65</td>
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<td>415 ± 65</td>
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<td>24.4</td>
<td>700</td>
<td>1.90</td>
<td>416</td>
<td>435 ± 75</td>
</tr>
</tbody>
</table>

B. Carbon

In order to measure the cross section for antiprotons on carbon a somewhat different method was tried. This centered around the use of the "live" target, X consisting of a 5-gallon liquid scintillator located behind Counter F (see Fig. 7). Each time an antiproton was selected by the time-of-flight system, the pulse produced by this large scintillator was photographed. By pulse-height analysis, antiprotons that interacted inelastically could be separated from those that either scattered elastically or passed through without interaction. Simultaneously the 13-inch final counter L was located beyond the target in order to detect transmitted antiprotons. The spectrum of pulse heights in X for 330 incident antiprotons of momentum 1.4 Bev/c with L in "good" geometry ($\theta_{1/2} = 2.63^0$) is shown in Fig. 8. Pulses are separated into two groups according to whether or not a coincident pulse occurred in L. The sharply peaked upper spectrum of Fig. 8 indicates that L detects principally non-interacting and forward-scattered antiprotons. A small number of secondaries associated with inelastic events in X (larger pulses) are detected by L.
On the other hand, events that are not detected in L are principally inelastic, as is indicated by the broad lower spectrum of Fig. 8. The peak in this spectrum is attributed to antiprotons that scatter elastically at angles large enough to miss counter L.

Figure 9 shows a similar spectrum obtained for 1959 antiprotons incident upon X with L placed in "poor" geometry ($\theta_1/2 = 25^\circ$). The broad background of the upper spectrum of Fig. 9 indicates that relatively more secondaries are detected by L, and the absence of a peak in the lower spectrum indicates that elastically scattered antiprotons are contained within L.

From the spectra of Fig. 8 we have determined the total carbon-antiproton cross section. Results of the cross-section measurements for hydrogen described in Section V have been used to correct the observed transmission of toluene ($C_7H_8$) to obtain the transmission for pure carbon.

From the spectra of Fig. 9 we have determined the inelastic carbon-antiproton cross section. Correction for hydrogen absorption has been made with the assumption that the proton-antiproton cross section is three-fourths inelastic. The justification for this is that, as will be seen, the inelastic antiproton cross section for carbon, and probably for beryllium, is considerably larger than the elastic. Since the total correction for hydrogen absorption amounts to only 15% of the carbon-antiproton cross section, the uncertainty introduced by this assumption is small.

The forward-scattering correction to the total cross-section measurement has been made, as for the beryllium measurements, by assuming that the region of interaction is an absorptive disk. The correction, although rather large, is relatively independent of the assumed radius of interaction. The value for the corrected total cross section $\sigma_{\text{corr}}^{\text{C}}$ given in Table III, is obtained for that radius which gives a computed value for the inelastic cross section equal to the measured value. The table includes as well the results of similar measurements at 0.9 Bev/c. $T$ is the kinetic energy of the antiproton at the center of the carbon (toluene) target and is uncertain by $\pm 5\%$. The expressed uncertainties in the cross sections are statistical only.

C. Lead

The desirability of extending the measurement of antiproton cross sections to elements other than carbon suggested the use of water inserts in the toluene scintillator. This might be especially helpful for heavy elements, for which the performance of good-geometry attenuation experiments is
complicated by the large multiple Coulomb scattering produced by thick targets.

To try this method, five equally spaced half-inch lead wafers were placed in

X (dashed outlines in Fig. 7).

From the transmission of X for antiprotons with and without lead inserts, the inelastic antiproton-lead cross section has been computed to be

2330 mb ± 285 mb at 650 Mev. The expressed uncertainty is statistical only. Other uncertainties in the lead-wafer experiment are probably greater than

in the carbon experiment. The presence of the wafers reduces the light-
collection efficiency and the uniformity of the scintillator; some self-absorption

of inelastic events occurs in the wafers; and finally the larger Coulomb scattering associated with the lead target makes the final counter less helpful in

separating elastic and inelastic events.

<table>
<thead>
<tr>
<th>$T_p$ (Mev)</th>
<th>$\theta_{1/2}$ (degrees)</th>
<th>$\sigma_{in}$ (mb)</th>
<th>$\sigma_{T_{obs}}$ (mb)</th>
<th>$\sigma_{T_{cor}}$ (mb)</th>
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<tr>
<td>700</td>
<td>25</td>
<td>436 ± 19</td>
<td>575 ± 59</td>
<td>557 ± 79</td>
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<tr>
<td>700</td>
<td>2.64</td>
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<td></td>
</tr>
<tr>
<td>300</td>
<td>3.55</td>
<td>568 ± 102</td>
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</tr>
<tr>
<td>300</td>
<td>3.95</td>
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</table>

**CONCLUSIONS**

The total proton-antiproton cross section is about 100 mb in the energy range of 300 to 700 Mev. This is considerably larger than the nucleon-nucleon cross sections for the same range of bombarding energies (see Fig. 6), and is apparently a direct consequence of the annihilation interaction. This interpretation is supported by measurements with a "live" target which show that in carbon the inelastic cross section is about twice the elastic cross section. Annihilation processes are a large part of these inelastic events, as indicated by the pulse-height spectrum (see Fig. 9). It is not surprising that we find relatively fewer inelastic interactions involving meson production without annihilation. These interactions are expected to occur through processes
similar to those operating in the nucleon-nucleon and pion-nucleon interactions, for which the high-energy inelastic cross sections are about 30 mb. Direct observation has shown that the charge-exchange cross section for antiprotons on CH is of the order of a few millibarns.

Comparison of our value of 484 ± 50 mb for the total antiproton-beryllium cross section at 500 Mev and the previous value of 355 ± 99 mb for the cross section obtained in a "poor" geometry experiment indicates that for beryllium also the inelastic antiproton cross section is probably considerably larger than the elastic.

Part of the difference between the nucleon-nucleon and nucleon-antinucleon cross section may follow from the large energy available (approximately 2 Bev) in the annihilation process. This factor, however, is not by itself sufficient to account for the large difference when we recall that for the p-p interaction at 5.3 Bev bombarding energy, where the center-of-mass energy is about the same as that of the nucleon-antinucleon system being considered, the total cross section is actually somewhat less than that at 0.8 Bev bombarding energy. Therefore, the large magnitude of the nucleon-antinucleon cross section, as compared with the nucleon-nucleon cross section, seems to be a characteristic of the basic nucleon-antinucleon interaction. An interesting approach in arriving at a theoretical formulation for such an interaction has been followed by Durr and Teller.

In the description of high-energy nucleon-nucleon and pion-nucleon collisions it is often convenient to speak of a radius of interaction. This is meaningful if the wavelength of the interacting particles is somewhat less than the radius R obtained, for example, by setting $\pi R^2 = \sigma_T$, where $\sigma_T$ is the measured total cross section. Proceeding similarly, we see that the antiproton-proton interaction is characterized by a "radius" about equal to the spacing between nucleons in the nucleus, so that we expect the nucleus to be relatively opaque to antiprotons. The extent of the interaction outside the nucleus is determined by interaction with nucleons on the surface. Consequently, in interactions with nuclei the ratio between the cross section for antinucleons and that for nucleons is expected to be smaller for the heavier nuclei. This is consistent with our observation that the inelastic antiproton-lead cross section is only 1 to 1.5 times the proton-lead cross section measured by Chen, Leavitt, and Shapiro, while for the lighter elements the factor is about 2.

The yield of antiprotons produced from 6-Bev protons incident upon a beryllium target is a strong function of antiproton energy, and is in fair agreement with the phase-space calculations.

Uncertainties given in each case are statistical only. Certain systematic uncertainties have been discussed separately in connection with the particular results.
ACKNOWLEDGMENTS

We take this opportunity to thank Dr. Edward J. Lofgren and the Bevatron operating staff for their invaluable cooperation. The help of Laurence S. Belier, Charles A. Coombes, Fred H. G. Lothrop, and Douglas Parmentier during the experiment is greatly appreciated. The liquid hydrogen target was designed by William M. Salsig and Garth E. Cook. Marion J. Jones was responsible for the design and operation of the numerous magnet power supplies. A group working with Felix C. Caldera built much of the electronics.

This work was done under the auspices of the U. S. Atomic Energy Commission.
REFERENCES


FIGURE CAPTIONS

Fig. 1. Antiproton selecting system. Q₁ through Q₅ are three-element quadrupole lenses and A₁ and A₂ are beam-deflecting magnets. A through F are plastic scintillation counters.

Fig. 2. Block diagram of basic electronics. A through L are scintillation counters; C₁ through C₆ are coincidence circuits; D₁ through D₄ are discriminators. M₁ and M₂ are monitors of the internal target and the magnetic channel flux, respectively. Amplifiers are not shown.

Fig. 3: Delay curve of time-of-flight selector at 1.4 Bev/c. Calculated delays for π mesons, K⁺ mesons, and antiprotons are shown on the horizontal axis. Coincidence C₁C₂ is made between the outputs of the two threefold coincidence circuits.

Fig. 4. Diagram of liquid hydrogen target construction.

Fig. 5. Layout of attenuation experiment with hydrogen target.

Fig. 6. Total antiproton-proton cross-section results. Uncertainties given are statistical only. Cross sections for p-p and p-n interactions are shown for comparison.

Fig. 7. Liquid scintillator target assembly. The dashed outlines indicate the location, when in place, of water inserts of target material.

Fig. 8. Pulse-height spectra in X for incident 1.4-Bev/c antiprotons. The 330 events are separated according to whether or not a coincident count occurred in a scintillator, L, which subtended at X an angular half width of 2.65°.

Fig. 9. Pulse-height spectra in X for incident 1.4-Bev/c antiprotons. These 1959 events are also separated as in Fig. 8, but with L subtending a half angle of 25° in this case.
Fig. 1
TO SCALERS

Fig. 2
Fig. 3
LIQUID H₂ TARGET
8" DIA. 62" LONG

INCIDENT ANTIPROTONS

4" x 4" SCINTILLATOR

100"

13" DIA.

PLASTIC SCINTILLATOR

Fig. 5
Fig. 6

<table>
<thead>
<tr>
<th>$T_p$ (bev)</th>
<th>$\sigma_T$ (mb)</th>
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<td>97 ± 4</td>
</tr>
<tr>
<td>0.700</td>
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Fig. 7
Fig. 8
Fig. 9