Further work is being done to extend the measurements to the other resonances of W^{183} and to other nuclides as well.

* Work performed under contract with U. S. Atomic Energy Commission.

[1] H. H. Landon and R. Rae, Phys. Rev. **107**, 1333 (1957).
[2] J. E. Mack, Revs. Modern Phys. **22**, 64 (1950).
[3] D. Strominger, University of California Radiation Laboratory Report UCRL-3374, 1956 (unpublished).
[4] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).
[5] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 647.
[6] Schwartz, Pilcher, and Schectman, Bull. Am. Phys. Soc. Ser. II, **1**, 187 (1956).
[7] R. Chrien and R. L. Zimmerman, Bull. Am. Phys. Soc. Ser. II, **3**, 19 (1958).
[8] F. B. Simpson and R. G. Fluharty, Bull. Am. Phys. Soc. Ser. II, **3**, 176 (1958).

Antiproton-Hydrogen Scattering and Inelastic Scattering from Complex Nuclei*

GERSON GOLDHABER,† THEODOR KALOGEROPOULOS, AND REIN SILBERBERG

Department of Physics and Radiation Laboratory, University of California, Berkeley, California

(Received April 21, 1958)

IN the study of antiproton interactions in nuclear emulsions a total of 413 antiproton annihilation stars have been found to date.[1–4] Most of these data come from emulsion exposures to enriched antiproton beams[4,5] at the Bevatron. In all this work the antiprotons are incident on the emulsion stacks with a kinetic energy of 200 to 250 Mev. As described earlier, the antiproton tracks are picked up near the entrance edge of the stack and followed along the track until they either interact in flight or come to rest.[1] Of the 413 antiproton stars observed, 217 came to rest and gave annihilation stars at rest, while 196 annihilated in flight (see Table I for further details). The interactions in flight, which determine the cross section, range in kinetic energy from 230 to 20 Mev with an average energy (weighted according to path length) of $\sim$150 Mev. In this note we would like to discuss the rare types of antiproton interactions that do *not* lead to annihilation, namely the $\bar{p}$-H scattering events and the antiproton inelastic scattering events. The elastic scattering of antiprotons from free hydrogen nuclei can be identified uniquely in photographic emulsions from the kinematics of the events.

TABLE I. Number of antiproton interaction events observed and emulsion path length scanned.

Emulsion type	Path length (cm)	Path length (g cm^{-2}) Ag	Br	C, O, N	H	Number of interactions: $\bar{p}$-annihil. stars in flight	at rest	$\bar{p}$-H scatt.	$\bar{p}$ inelastic scatt.
G5, K5	2286[a]	4180	3110	1380	122	124	159	7	3+1
G5, 3× diluted[b]	1506[c]	1390	1140	1360	114	72	58	3	5
Total	3792	5570	4250	2740	236	196	217	10	8+1

[a] This path length includes 602 cm from work with unseparated antiproton beams (Antiproton Collaboration Experiment, reference 1; Rome group, reference 2; Uppsala group, reference 3) as well as results with a separated antiproton beam (1394 cm) reference 4 and doubly separated antiproton beam (290 cm) (reference 5).
[b] Ilford G5 3× diluted is an emulsion with three times the normal gelatine concentration, density = 2.66 g cm^{-3}.
[c] This path length comes entirely from stack 88 exposed in the doubly separated antiproton beam (reference 5).

TABLE II. Antiproton-hydrogen scattering events.[a]

Event number	$\bar{p}$ scatt angle (c.m. system) (degrees)	$\bar{p}$ energy (lab system) (Mev)
3S-34	17.6	175
3S-326	30.8	120
3-26	33.4	72
6-6[b]	44	175
3S-22	48.5	184
3S-38	50	142
3S-244	50	230
3S-140	53	135
3S-1002	79	161
3S-293	117.8	208

[a] Five of these events have been reported in reference 4.
[b] From Uppsala Group (reference 3).

Ball and Chew have recently proposed a model for the antinucleon-nucleon interaction in terms of a modified nucleon-nucleon potential.[6] Their results, owing to the nature of the approximation methods used in the evaluation of the phase shifts, are valid at moderate energies, namely $T_{\bar{p}} \lesssim 200$ Mev. In addition Fulco[7] has evaluated the differential cross section based on the Ball and Chew phase shifts. The angular distribution is characteristic of a single diffraction peak, with a minimum at $\theta_{\text{c.m.}} \sim 90°$ and a very small cross section in the backward direction. The integrated forward-to-backward cross-section ratio is about 14 to 1. At present our statistics are still very limited; however, the agreement with the above predictions is excellent. From the 10 $\bar{p}$-H elastic scattering events found in emulsions to date, we obtain a scattering cross section $\sigma_{\bar{p}\text{-H scatt}} = 71_{-21}^{+30}$ mb. As is shown in Table II, nine of the events lie in the forward hemisphere while one lies in the backward hemisphere in the c.m. system. A $\bar{p}$-H scattering event can be recognized reliably when the recoiling proton is at least 3 μ in range. This introduces a cutoff angle for antiproton scattering of $\theta_{\text{c.m.}} = 4.3°$ at 230 Mev and $\theta_{\text{c.m.}} = 5.4°$ at 150 Mev (our average energy), and $\theta_{\text{c.m.}} = 12°$ at 30 Mev. For purposes of this experiment the effect on the cross section is negligible.

The $\bar{p}$-H annihilation events can, in general, not be uniquely identified in photographic emulsions. However, we can single out that group of stars which must contain the $\bar{p}$-H annihilation events. The requirement is for a star in flight with an *even* number of charged pions and no visible nuclear excitation. Among 219 stars in emulsion analyzed to date,[8] 93 of which occurred in flight, we have found 5 stars which fulfill those

TABLE III. Inelastic antiproton scattering events from complex nuclei.

Event number	$\theta_{\bar{p}}$ $\bar{p}$ scatt. angle (lab system) (degrees)	$T_{\bar{p}}$ $\bar{p}$ energy, incident (Mev)	$T_{\bar{p}}'$ $\bar{p}$ energy after scattering (Mev)	$\Delta T_{\bar{p}}/T_{\bar{p}}$	Additional prongs[c]
3S-294	11	$\sim$260	246	0.05	One; $T_{p+}=5.2$ Mev, $\theta_{p+(\text{lab})}=53°$. Deviation from coplanarity 1°.
1-4[a]	16	$\sim$224	$\sim$210	0.06	Two; $T_{p+}=5.8$ Mev, and recoil 1.6 μ.
3S-254	16	$\sim$200	188	0.06	One; $T_{p+}=1.2$ Mev, $\theta_{p+(\text{lab})}=70°$. Deviation from coplanarity 16°.
3S-1022	28	67±5	31	0.5	None.
3S-228	37	$\sim$150	115	0.2	Two; $T_{p+}=2.2$ Mev, and recoil 5 μ.
3-2[b]	47	163±10	132	0.2	Two; $T_{p+}=1.3$ Mev and $T_{p+}=0.6$ Mev.
3S-249	47	$\sim$35	17.5	0.5	Two; $T_{p+}=1.2$ Mev and $T_{p+}=0.7$ Mev.
3S-312	64	$\sim$46	31.5	0.3	One; $T_{p+}=6$ Mev, $\theta_{p+(\text{lab})}=49°$. Deviation from coplanarity 14°.
3S-88	64	160±10	133	0.2	One; recoil 2 μ.

[a] Published previously (reference 1). In this event the antiproton leaves the stack after scattering and its identity as an antiproton can thus not be uniquely established. We will count it as 0.5 event here.
[b] Published previously (reference 1).
[c] The energies are assigned on the assumption that the observed prongs are protons.

conditions: two with charged-pion multiplicity $N_{\pi^\pm}=2$, two with $N_{\pi^\pm}=4$, and one with $N_{\pi^\pm}=6$. These events thus represent an upper limit to the number of $\bar{p}$-H annihilation events.[9] The corresponding path length in hydrogen is 97 g cm^{-2}, giving a $\bar{p}$-H annihilation cross section, $\sigma_{\bar{p}\text{-H annih}} \leqslant 86_{-37}^{+58}$ mb.

In addition to the above-mentioned events we have observed 8 or 9 inelastic scattering events of antiprotons with complex nuclei (see Table III). In general these correspond to rather small energy loss and a fairly large scattering angle. In comparing these with the elastic scattering events from complex nuclei,[10] we have found about 100 events in the angular interval 2 degrees to 25 degrees but only one event with a scattering angle greater than 25 degrees. Thus the larger-angle scattering appears to be principally inelastic. Our criterion for the inelasticity of a scattering event was visible nuclear excitation or ionization change corresponding to an energy loss of $\Delta T_{\bar{p}}/T_{\bar{p}} \geqslant 0.2$. It is, however, possible that some additional inelastic scattering events with $\Delta T_{\bar{p}}/T_{\bar{p}} < 0.2$ may be present among the elastic scattering events observed.

On an independent-particle model the inelastic scattering events correspond to the elastic scattering from a single bound nucleon. As such it should reflect the antiproton-nucleon elastic scattering cross section. We see that although $\sigma_{\bar{p}\text{-H scatt}}$ and $\sigma_{\bar{p}\text{-H annih}}$ are roughly comparable, the inelastic scattering is strongly suppressed, and amounts to $\sim$4.3% of the annihilation events in flight. The suppression of the inelastic scattering process must be due to two effects: (a) the Pauli exclusion principle, which is particularly effective here because of the strong forward peaking of $d\sigma_{\bar{p}\text{-H scatt}}/d\Omega$; (b) the high annihilation probability, which frequently leads to the annihilation of an antiproton in the same nucleus as that in which scattering took place. The effect observed here is similar to that observed in the antineutron production in complex nuclei by charge exchange of antiprotons, *viz.* $\bar{p}+$"p"$\rightarrow\bar{n}+n$.[11] The latter also involves the re-emission of an antinucleon from the complex nucleus and has been shown to be independent of the nuclear size. Such re-emission can presumably occur only in a fringe collision in the low-density region of the nucleus. The inelastic scattering cross section per emulsion *nucleus* (excluding hydrogen) is $\sigma_{\bar{p}\text{ inel}}=45_{-16}^{+22}$ mb and is to be compared with $\sigma_{\bar{p}\text{-H scatt}}=71_{-21}^{+30}$ mb. We see that the two cross sections are comparable within the experimental error, which is consistent with an optical-model calculation performed for antineutron production.[12]

We wish to acknowledge the help given in the exposure to the enriched antiprotons beams by Professor Emilio Segrè and members of his group and in particular by Mr. Lewis Agnew. The help by Dr. Edward Lofgren and members of the Bevatron crew is also greatly appreciated. Finally, this work would not have been possible without the conscientious efforts of Mr. Jim Glass, Mrs. Lora Langner, Mr. Kirmach Natani, Mrs. Evelyn Rorem, Mrs. Elizabeth Russell, Mrs. Mary Lou Santos, Miss Charlotte Scales, and Mrs. Louise Shaw.

* Work supported by the U. S. Atomic Energy Commission.
† Supported in part by the Adolph C. and Mary Sprague Miller Institute of Basic Research of the University of California.

[1] Barkas, Birge, Chupp, Ekspong, Goldhaber, Goldhaber, Heckman, Perkins, Sandweiss, Segrè, Smith, Stork, Van Rossum, Amaldi, Baroni, Castagnoli, Franzinetti, and Manfredini, Phys. Rev. **105**, 1037 (1957).
[2] Amaldi, Castagnoli, Ferro-Luzzi, Franzinetti, and Manfredini, Nuovo cimento **5**, 1797 (1957).
[3] Ekspong, Johansson, and Ronne, University of Uppsala (to be published).
[4] Chamberlain, Goldhaber, Janneau, Kalogeropoulos, Segrè, and Silberberg, *Proceedings of the 1957 Padua-Venice International Conference on Mesons and Recently Discovered Particles, September 22–28, 1957* [Nuovo cimento (to be published)].
[5] Agnew, Elioff, Fowler, Gilly, Lander, Oswald, Powell, Segrè, Steiner, White, Wiegand, and Ypsilantis, Phys. Rev. **110**, 994 (1958).
[6] J. S. Ball and G. F. Chew, Phys. Rev. **109**, 1385 (1958).
[7] J. R. Fulco, Phys. Rev. **110**, 784 (1958).
[8] The analysis of all the 219 annihilation stars will be published shortly.
[9] In addition to the five events with an even number of charged pions we have found two events with an odd number ($N_{\pi^\pm}=3$). These must presumably be looked upon as background non-H events.
[10] G. Goldhaber and J. Sandweiss. *Proceedings of the 1957 Padua-Venice International Conference on Mesons and Recently*

Discovered Particles, September 22–28, 1957 [Nuovo cimento (to be published)].
[11] Button, Elioff, Segrè, Steiner, Weingart, Wiegand, and Ypsilantis, Phys. Rev. **108**, 1557 (1957).
[12] Richard C. Weingart, thesis, University of California Radiation Laboratory Report UCRL-8025, October, 1957 (unpublished).

Elastic Scattering of Antiprotons from Complex Nuclei*

GERSON GOLDHABER† AND JACK SANDWEISS‡
Physics Department and Radiation Laboratory, University of California, Berkeley, California
(Received May 5, 1958)

IN continuing the study of the interactions of antiprotons in nuclear emulsions, we have examined a total length of 16.0 meters of antiproton path in the energy region 50 to 200 Mev. We report here on our measurements of the elastic scattering of antiprotons in nuclear emulsion. The total path length was obtained from the various exposures to the unseparated antiproton beam[1] and from a separated-beam exposure.[2]

In these experiments, stacks of 600-micron Ilford G.5 nuclear emulsion have been exposed to antiprotons from the Berkeley Bevatron. For the purposes of the elastic-scattering measurement we have selected only tracks due to antiprotons identified by means of an annihilation star. In the range interval corresponding to 50 to 200 Mev, these tracks were carefully examined for scattering events with projected angle of scattering greater than 2°. A scattering event was accepted as elastic if there was no visible change of grain density and no visible recoil or excitation of the struck nucleus. The grain-count criterion adopted eliminates inelastic scattering events with $\Delta T_{\bar{p}}/T_{\bar{p}} \geqslant 0.2$. However, some slightly inelastic scattering events ($\Delta T_{\bar{p}}/T_{\bar{p}} < 0.2$) may still be present in our data. Scattering from free hydrogen in the emulsion and inelastic scattering from complex nuclei are discussed in a separate communication.[3]

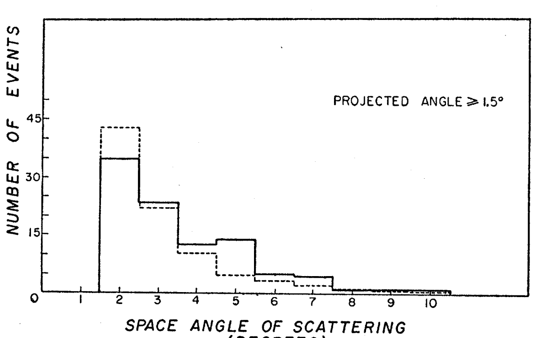

FIG. 1. Number of scattering events with projected angle greater than 1.5° as a function of the space angle of scattering. The solid histogram shows the results on 8.1 meters of antiproton track in the energy range 50 to 200 Mev, and the dashed histogram shows the distribution expected from point-nucleus Rutherford scattering.

TABLE I. Numbers of antiproton scattering events with projected angle ⩾2° observed per 30-Mev interval in a 16-meter path length in emulsion.

Space angle of scattering (degrees)	Energy interval (Mev) 50–80	80–110	110–140	140–170	170–200	Total, 50–250
2–4	18	7	11	8	7	51
4–6	6	6	6	6	3	27
6–9	4	4	4	2	2	16
9–12	3	2	1	2	2	10
12–18	1	2	1	0	0	4
18–24	0	0	2	0	0	2
24–180	0	1	0	0	0	1
2–180	32	22	25	18	14	111
Path length (cm)	146	222	310	414	508	1600

We have checked our scanning efficiency both by rescanning and by measuring a sample in which we included projected angles greater than 1.5°. In the latter case we may compare the results with point-nucleus Rutherford scattering. Figure 1 shows the results on 8.1 meters of antiproton track. For scattering events with projected angle greater than 2° the scanning efficiency is 100%. A total of 111 such scattering events were found in 16 meters of path length. Table I lists the number of antiproton scattering events for various antiproton energy intervals as well as the corresponding path-length distribution. The number of events observed in this experiment is insufficient to allow a comparison with theory in the separate energy intervals; we shall thus consider the data in the entire energy interval 50 to 200 Mev. The histogram in Fig. 2 shows the experimental angular distribution (see Table II). Of the 111 scattering events, only one occurred at an angle greater than 25°. The solid curve represents the

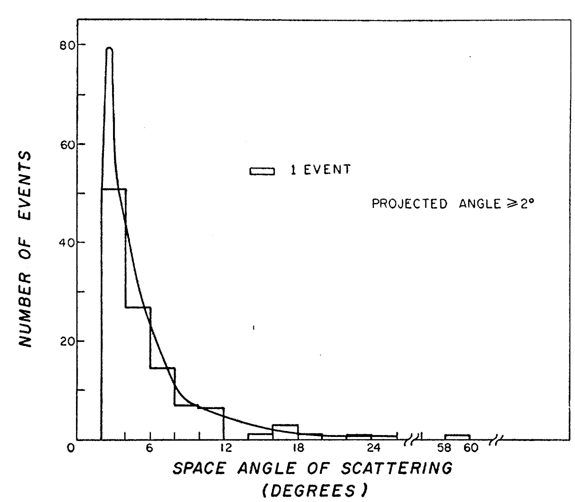

FIG. 2. The angular distribution for the entire energy interval 50 to 200 Mev. The histogram shows the observed number of elastic scattering events with projected angle greater than 2°. The solid curve shows the distribution expected from the charged-black-sphere model. Solid-angle corrections, to take account of the 2° cutoff criterion in projected angle, have been applied to the computed curve.