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ANTIPROTON-HYDROGEN SCATTERING AND INELASTIC SCATTERING FROM COMPLEX NUCLEI[†]

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In the study of antiproton interactions in nuclear emulsions a total of 413 antiproton annihilation stars have been found to date.[1, 2, 3, 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 ~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.

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 $\theta_{cm} \sim 90^{0}$ 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 $\sigma_{\bar{p}\text{-H scatt}} = 71^{+30}_{-21}$ 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 $\theta_{cm} = 4.3^{\circ}$ at 230 Mev and $\theta_{cm} = 5.4^{\circ}$ at 150 Mev (our average energy), and $\theta_{cm} = 12^{\circ}$ 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 p-H annihilation events. The requirement is for a star in flight with an <u>even</u> 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 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, $\sigma_{\bar{p}\text{-H annih}} \lesssim 86^{+58}_{-37}$ mb.

In addition to the above-mentioned events we have observed 8 or 9 inelastic scattering events of antiprotons have 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 $\Delta T_{\bar{p}}/T_{\bar{p}} \gtrsim 0.2$. 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 $\sigma_{\bar{p}H\text{ scatt}}$ and $\sigma_{\bar{p}H\text{ annih}}$ are roughly comparable, the inelastic scattering is strongly suppressed, and amounts to ~ 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. $\overline{p} + \text{"N"} \rightarrow \overline{N} + p$.[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 $\sigma_{\overline{p}\,\text{inel}} = 45^{+22}_{-16}$ mb and is to be compared with $\sigma_{\overline{p}\text{H scatt}} = 71^{+30}_{-21}$ 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 antiproton beams by Prof. 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 Laugner, Mr. Kirmach Natani, Mrs. Evelyn Rorem, Mrs. Elizabeth Russell, Mrs. Mary Lou Santos, Miss Charlotte Scales, and Mrs. Louise Shaw.

References

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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, Preprint (unpublished).
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 (in publication).
5. Agnew, Elioff, Fowler, Gilly, Lander, Oswald, Powell, Segrè, Steiner, White, Wiegand and Ypsilantis, Phys. Rev. (in press).
6. J. S. Ball and G. F. Chew, Phys. Rev. 109, 1385 (1958).
7. J. R. Fulco, Phys. Rev. (in press).
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 (in publication).
11. Button, Elioff, Segrè, Steiner, Weingart, Wiegand, and Ypsilantis, Phys. Rev. 108, 1557 (1957).
12. Richard C. Weingart, Antineutron Production by Charge Exchange (Thesis), UCRL-8025, Oct. 1957.

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

Emulsion type	Path length (cm)	Path length (g cm^{-2})				Number of interactions			
						p-annihil stars			
		Ag	Br	C, O, N	H	in Flight	at rest	p-H scatt	p inelastic scatt.
G5, K5	2286[a]	4180	3110	1380	122	124	159	7	3+1
G5, 3X Diluted[c]	1506[b]	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, Ref. 1; Rome group, Ref. 2; Uppsala group, Ref. 3) as well as results with a separated antiproton beam (1394 cm) Ref. 4 and doubly separated antiproton beam (290 cm) (Ref. 5).

[b] This path length comes entirely from stack 88 exposed in the doubly separated antiproton beam (Ref. 5).

[c] Ilford G5 3X diluted is an emulsion with three times the normal gelatine concentration, density = 2.66 g cm^{-3}.

Table II. Antiproton-hydrogen scattering events[a]

Event number	$\bar{p}$ Scatt Angle (cm 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 at the 1957 Padua-Venice International Conference on "Mesons and Recently Discovered Particles" September 22-28, 1957 (Ref. 4).

[b] From Uppsala Group (Ref. 3).

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

(a) Published previously (Ref. 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 (Ref. 1).