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Interactions of Antiprotons in Nuclear Emulsion

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Summary. In the last years many nuclear emulsion experiments with machine-produced antiprotons have been performed. The present publication is a small contribution to the increasing statistics on antiproton data in nuclear emulsion.

The principal experimental results obtained in the present experiment are the following:

The annihilation mean free path was found to be $17.1^{+6.0}_{-4.4}$ cm for the energy interval between 40 MeV and 200 MeV.

The average number of emitted charged pions per star was $1{\cdot}80 \pm 0{\cdot}35$ for the stars in flight and 2.13 ± 0.38 for the stars at rest.

Among the 30 analyzed annihilation stars 1 probable K-meson was found.

The angular distribution of the elastic scatterings down to a scattering angle of 1° is obtained.

Exposure

A stack of 175 stripped Ilford G-5 emulsions was exposed to the 700 MeV/c momentum negative particle beam of the Bevatron. The size of the plates was 15×22.5 cm². The flux of background pions was of the order of 2.3×10^5 π/cm² at the center of the beam. The antiprotons entered the plates perpendicular to the leading edge and came to rest after a mean path of 12.9 cm, corresponding to a mean energy of the antiprotons of 230 MeV at the entrance into the emulsions.

Scanning procedure

The tracks were chosen on the basis of ionization and of the angle of entrance relative to the angle of the background pions. The tracks were picked up along a line perpendicular to the direction of the beam at about 5 mm from the leading edge. The expected ionization for anti-

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proton tracks of the given momentum was about twice minimum. All tracks which were about twice minimum ionization and which satisfied the entrance angle criteria within $\pm 5°$ degrees were followed until they either interacted in flight or came to rest in the emulsion. In this manner were found 32 antiprotons, of which 15 underwent an annihilation in flight and 17 interacted at rest. Since there was an appreciable flux of protons entering the edge and stopping throughout the body of the stack, no $\bar{p}_\varrho$ could be definitely identified.

Path length

The total followed antiproton path length was 326 cm. Fig. 1 shows the scanned path length as a function of the antiproton energy.

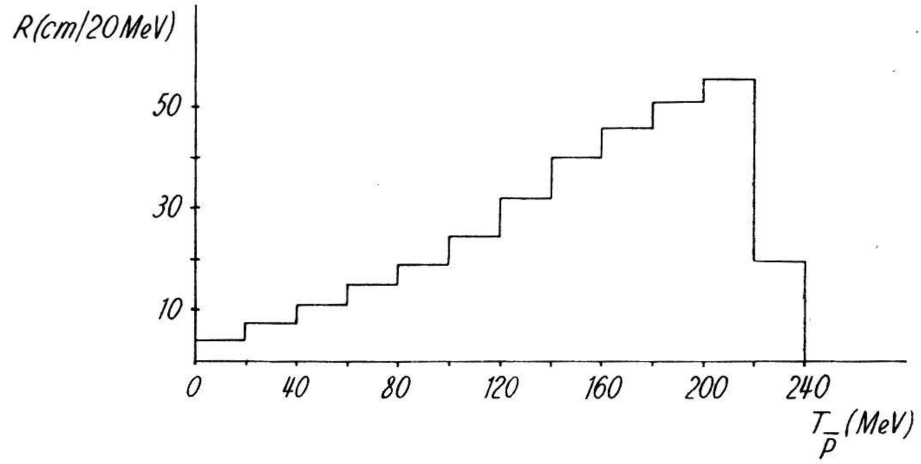

Fig. 1
Scanned antiproton path length as function of the antiproton energy

The antiproton energy at the point of the annihilation was determined by ionization measurements. We did not attempt to measure energies lower than 40 MeV.

Annihilation mean free path

As was already mentioned, we cannot prove that interactions which were classified as 'at rest' were really at rest. It is believed that it is possible to detect interactions in flight visually down to about 6 mm residual range, which corresponds to an antiproton kinetic energy of 40 MeV. Of the 17 cases classified as $T_p \leq 40$ MeV, 10 could be taken as at rest by the characteristic behaviour of the track in the last few microns. According to a precise measurement*) of the kinetic energy at the point of annihilation it was deduced that $< 5\%$ of those that ap-

*) O. Chamberlain, G. Goldhaber, L. Jauneau, Th. Kalogeropoulos, E. Segrè and R. Silberberg, The Antiproton-Nucleon Annihilation Process II, UCRL-8424 (1958).

pear 'at rest' were actually interactions in flight with $10 < T_{\bar{p}} < 40$ MeV. We considered the remaining 7 events also at rest.

Table 1 gives the annihilation mean free path for different intervals of primary antiproton energy between 40 and 200 MeV.

Table 1

Mean free path for annihilation in the energy interval between 40 and 200 MeV primary antiproton energy

$T_{\bar{p}}$ (MeV)	path length (cm)	number of events	m. f. p. (cm)
40–70	18.2	1	18.2^{+73}_{-12}
70–100	26.9	2	13.5^{+25}_{-8}
100–150	75.3	7	10.8^{+6}_{-4}
150–200	118.7	4	29.7^{+27}_{-13}
40–200	239.1	14	$17.1^{+6.0}_{-4.4}$

(1 event was found at an energy of 230 MeV and 17 events had an energy below 40 MeV and were taken as at rest)

Small angle scattering

317 cm of track length were followed and all elastic scatterings with a projected angle $\geqslant 1°$ were recorded. The cut off was made at a residual range of 5 mm which corresponds to an energy of 35 MeV. To test the scanning efficiency all tracks were followed twice by different observers.

To obtain the angles in space we used the analytical relation between the angle in space and its projection. If we denote the angular distribution in space by $F(\Theta)$ and the corresponding distribution of the projected angles by $f(\alpha)$, the relation is

$$f(\alpha) = \frac{2}{\pi} \int_{\alpha}^{\pi/2} \frac{F(\Theta)\, d\Theta}{\cos^2 \alpha \sqrt{\mathrm{tg}^2\, \Theta - \mathrm{tg}^2\, \alpha}} \cdot$$

The calculation of $F(\Theta)$ was done by numerical integration. We give the experimental distribution of the projected angles and the calculated distribution of the space angles in Fig. 2.

We compare the obtained distribution with the distribution calculated by assuming point-nucleus Rutherford scattering, where the Rutherford scattering curve is normalized to the same number of scattering in the interval between 1° and 2° where Coulomb scattering is predominant. We observe that between 1° and 2° the fit is quite good, while for higher angles there seems to be a difference between the two curves, perhaps due ta the finite size of the nucleus or to a possible destructive interference between Coulomb scattering and nuclear scattering.

Pions

All thin or grey secondary tracks were followed until the particles came to rest in the emulsion or until they left the stack or made an interaction in flight. Fast tracks which left the stack were gap-measured at the primary star and also at the point where they left the stack. This procedure aloowed us to identify most of the tracks, even the steep ones. In addition, flat tracks with a dip $< 20°$ in the unprocessed emulsion, were also scattered. In this way most fast particles could be identified. In

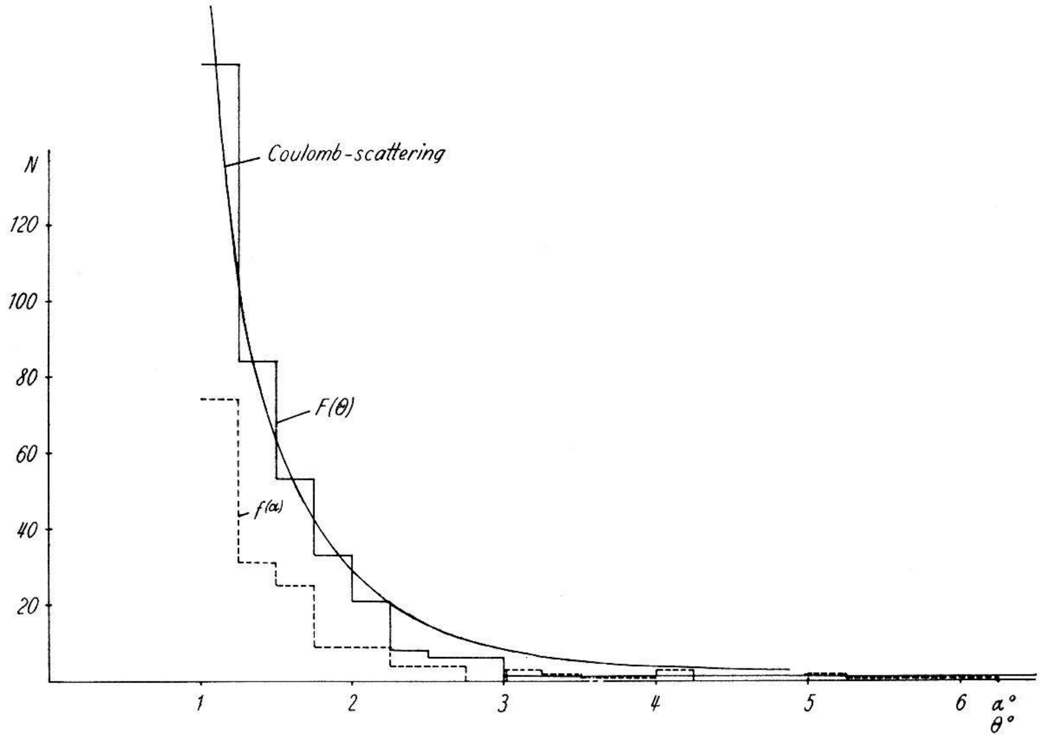

Fig. 2

some cases the particles were most likely to be pions, but the possibility that they were K-mesons could not be absolutely denied. Such particles however were counted as pions.

Table 2 gives a list of all unstable secondary particles emitted from the annihilation stars. It is noted when such a particle could be identified with certainty. In the other cases the most probable identity as well as other possible identities are listed, with their corresponding kinetic energies.

25 annihilation stars were associated with pion emission, 5 stars had no visible pions and 2 events were left out of the analysis, one which was situated in an endplate of the stack so that the secondaries could not be followed, and one star where a fast particle prong was so steep as to render any measurements on it impossible.

The average visible pion multiplicity is $32/15 = 2.13 \pm 0.38$ for the stars at rest and $27/15 = 1.80 \pm 0.35$ for the stars in flight.

Table 2

Unstable particles emitted from the annihilation stars

Event	$T_{\bar{p}}$	Identified particle kin. energy (MeV)		Most probable identity, kin. energy (MeV)		Other possible identity, kin. energy (MeV)	
1	0	π	103 ± 5				
		π	111 ± 9				
		π	215 ± 28				
		π	162 ± 9				
2	0	π	130 ± 10				
3	0	K	~ 285				
4	138	π^-	49				
		π	~ 93				
		π	86				
5	0	π	~ 80				
		π	~ 150				
				π	~ 110	K	~ 240
6	131	π^-	69				
		π	>150				
				π^+	150		
7	82	π	51				
8	0	π	~ 100				
		π	150 ± 20				
9	100	π^-	72				
11	0	π	265 ± 50				
		π	254 ± 63				
12	0	π	186 ± 27				
		π	~ 190				
				π	~ 100	K	~ 256
13	135	π	> 90				
15	0	π	~ 100				
		π^-	100				
		π	> 70				
		π	~ 150				
16	0	π	>150				
		π	>150				
				π	~ 90	K	~ 270
17	64	π	130 ± 15				
18	119	π	~ 175				
		π	~ 240				
		π	~ 330				
		π	~ 108				

Table 2 (continued)

Event	$T_{\bar{p}}$	Identified particle kin. energy (MeV)		Most probable identity, kin. energy (MeV)		Other possible identity, kin. energy (MeV)	
20	0	π	$\sim$280				
		π^+	61				
		π	130				
21	155	π^-	78				
		π	219				
		π	$>$360				
		π	$>$460				
23	98	π	$>$150				
25	0	π	293				
26	151	π^-	36				
		π	114				
27	0	π	56				
		π^-	32				
		π	$>$ 80				
		π	91 ± 15				
28	121	π	$>$ 70				
		π^+	98				
30	230	π^-	27				
		π	$>$100				
33	173			π	$\sim$ 50	K	$\sim$170
		π	108 ± 13				
34	0	π	77 ± 11				
		π	$>$150				

K-mesons

Among the particles emitted in the annihilations we did not observe any K-mesons either coming to rest or decaying in flight. But among the emitted fast particles, one track, on the basis of gap-length and scattering measurements, could only be explained as belonging to a K-meson. It is listed in table 2 as identified case. This ratio is in agreement with the value of $(3.5 \pm 1.5)\%$ obtained by CHAMBERLAIN et al. (see ref. page 560) In the case of 4 fast particles the possibility of a K-meson could not entirely be dismissed, due to large errors in the ionization measurements. Those tracks were too steep to allow scattering measurements. We considered those tracks as belonging to pions. If we take those 4 doubtful cases as K-mesons we get an upper limit for K-meson production of 5/30.

Visible energy release

The total available energy in an antiproton annihilation at rest is $Q = 1876$ MeV. This energy is released mainly in pions, evaporation particles and occasionally in strange particles. The energy given to pions is already listed in table 2. To obtain the energy given to evaporation particles the two laboratories engaged in the analysis of the events followed somewhat different criteria. The Berkeley team made gap count measurements

Table 3

Visible Energy Release in the Annihilation Stars

No.	$T_{\bar{p}}$	N_π	E_π	N_{ev}	N_{ko}	N_H	E_{ev}	E_{ko}	E_H	E_K	E_{vis}	W	E_{vis}/W
1	0	4	1151	7	1	8	274	135	409		1560	1868	0·84
2	0	1	270	0	0	0	0	0	0		270	1868	0·14
3	0	0	0	2	2	4	30	83	113	779	892	1868	0·48
4	138	3	648	4	2	6	129	87	216		864	2006	0·43
5	0	3	760	1	0	1	20	0	20		780	1868	0·42
6	131	3	790	3	3	6	62	219	281		1071	1999	0·54
7	82	1	191	10	1	11	158	91	249		440	1950	0·23
8	0	2	530	5	3	8	102	399	501		1031	1868	0·55
9	100	1	212	4	4	8	63	237	300		512	1968	0·26
10	0	0	0	4	2	6	63	190	253		253	1968	0·14
11	0	2	799	3	1	4	38	105	143		942	1868	0·50
12	0	3	896	0	0	0	0	0	0		896	1868	0·48
13	135	1	230	1	1	2	24	79	103		333	2003	0·16
14	177	0	0	4	2	6	84	203	287		287	1985	0·15
15	0	4	980	0	0	0	0	0	0		980	1868	0·52
16	0	3	810	1	0	1	20	0	20		830	1868	0·44
17	64	1	270	2	0	2	28	0	28		298	1932	0·16
18	119	4	1413	3	1	4	119	76	195		1608	1987	0·81
19	0	0	0	2	1	3	54	43	97		97	1868	0·05
20	0	3	891	2	0	2	23	0	23		914	1868	0·49
21	155	4	1677	0	0	0	0	0	0		1677	2033	0·82
23	98	1	290	6	3	9	119	258	377		667	1966	0·34
25	0	1	433	2	2	4	49	406	455		888	1868	0·47
26	151	2	430	6	9	15	141	554	695		1125	2019	0·56
27	0	4	820	3	0	3	54	0	54		874	1868	0·47
28	121	2	448	3	2	5	59	80	139		587	1989	0·30
29	0												not analyzed
30	230	2	407	9	6	15	213	453	666		1073	2098	0·51
31	0												not analyzed
32	188	0	0	3	0	3	52	0	52		52	2065	0·03
33	173	2	438	4	3	7	103	514	617		1055	2041	0·52
34	0	2	507	0	0	0	0	0	0		507	1868	0·27

on all the heavy tracks and was thus able to distinguish between protons, deuterons and alpha particles. The Berne group took all black tracks longer than 120 μ as protons, those between 30 μ and 100 μ as alpha particles and assigned to all shorter prongs a total energy of 20 MeV*).

Protons were given a binding energy of 8 MeV, alpha particles 4 MeV. Protons with an energy $\geqq$ 35 MeV were taken as knock-on particles. No attempt was made to say anything about the energy given to neutral particles, such as neutrons, neutral pions and K°-mesons.

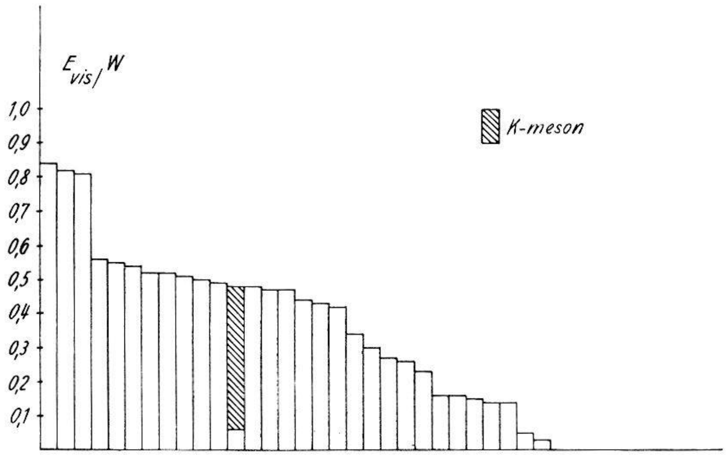

Fig. 3

Ratio of visible energy E_{vis} to total available energy W for the annihilation stars

Table 3 shows the number N_π of pions, their total energy E_π per star, the numbers of heavy prongs N_H consisting of evaporation particles N_{ev} and knock-on particles N_{ko}. Also given are their respective energies including binding energies E_H, E_{ev} and E_{ko}. In the case where a K-meson is suggested its total energy is given. E_{vis} is the total visible energy, W the total available energy $W = Q + T_{\bar{p}}$. The last collumn lists the ratio of visible energy to available energy. This ratio is also given in Fig. 3.

Acknowledgements

We are indebted to the Bevatron crew for making the exposure possible and to Dr. Warren Chupp who undertook the major responsibility of setting up the beam for the experiment. We want to thank the scanning technicians of both laboratories for their efforts which contributed much to the program.

*) J. Hornbostel and E. O. Salant, Phys. Rev. *102*, 502 (1956).