Session X

ANTIBARYON PHENOMENA

Chairman: E. Amaldi

CHAMBERLAIN: Introductory survey.

Below are listed the names of the people in the three main groups that have done most of the work I want to report:

1. Agnew, Button, Chamberlain, Elioff, Keller, Larson, Rogers, Segré, Steiner, Weingart, Wiegand, Ypsilantis
2. Cork, Lambertson, Piccioni, Wenzel
3. Barkas, Birge, Chupp, Ekspong, Goldhaber, Goldhaber, Heckman, Perkins, Sandweiss, Sergré, Smith, Stork, Van Rossum and Amaldi, Baroni, Castagnoli, Franzinetti, Manfredini

When we started to look into the problem of whether the antiprotons could be found, I tended to take a rather optimistic view because I had assumed that we had invariance under charge conjugation. This was, in a sense, an excellent guess because it provided the necessary impetus at the time, but it now turns out apparently not to be true. However, invariance under CPT fortunately has some of the needed properties: in particular the mass of an antiproton must be just the same as the mass of the proton, and for unstable particles the life of the particle and antiparticle must be the same.

Table 1 shows our present picture of the spectrum of the baryons and antibaryons. Of the particles in the table Ξ^0 as far as I know, has not been observed. Among the antiparticles only the antiproton and antineutron have been observed. We expect

Table 1

Known and hypothetical baryons and antibaryons

Strangeness:	-2	-1	0	1	2
Baryons (N 1)	$\Xi^{(\bar{0})}$	$\Sigma^{(\bar{0}+)}$, $\Lambda^{(0)}$	$N^{(0+)}$		
Antibaryons (N -1)			$\tilde{N}^{(\bar{0})}$	$\tilde{\Sigma}^{(+0-)}$, $\tilde{\Lambda}^{(0)}$	$\tilde{\Xi}^{(+0)}$

the other antibaryons would be produced in any reaction that could go via a strong interaction, provided we satisfy all of the usual conservation laws, including the conservation of baryons and of strangeness. For instance one could have $p + n \longrightarrow p + n + \Sigma^{+} + \tilde{\Sigma}^{+}$. The threshold for this reaction is 7.8 Bev, and now that the world has an accelerator above that energy I expect that such reactions will be observed fairly soon. I shall confine the rest of my talk to the observed antibaryons: the antiproton and the antineutron.

The identification of antiprotons is usually done by a determination of momentum by magnetic curvature, and a simultaneous determination of velocity, e.g. in counter experiments by time of flight and in emulsion by grain density. In emulsions there are additional types of measurement such as multiple scattering and range. Finally they are identified by the energy release at annihilation. Fig. 1 shows a recent spectrograph, which is rather similar to the first spectrograph used. From the target T a magnetic lens Q_1 and bending magnet M_1 bring the particles to a first focus at F_1. They are again bent by M_2 and focussed at F_2 by lens Q_2 finally entering at E the apparatus used to study the antiproton interactions. The only major changes from the earliest instrument were to use larger magnets, increase the aperture, and accept a poorer momentum definition to get a greater intensity. We also use what we call Fitch counters, i.e. Cerenkov counters with a velocity band pass. The Cerenkov light from relativistic particles cannot reach the photomultiplier tube because of total internal reflection. These counters serve to prevent fast mesons from getting into the electronic system.

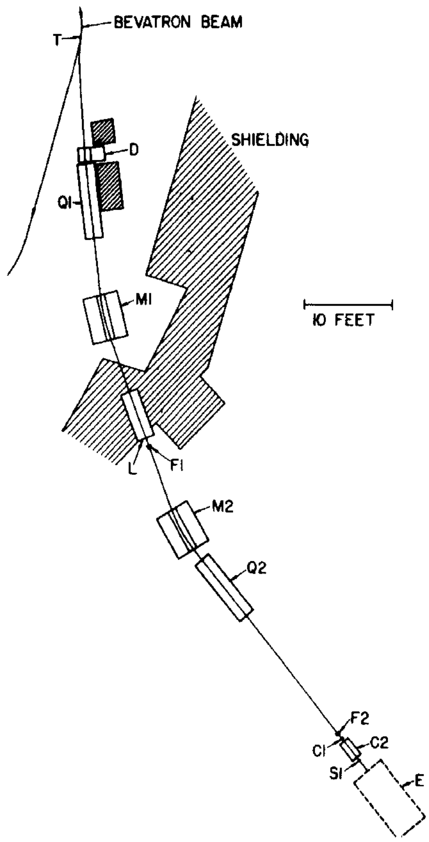

Fig. 1

This arrangement prevents some of the measurements we could otherwise make, but it is very convenient because of the high π^-/p^- ratio in the beam. Fig. 2 shows our apparatus for the identification of antineutrons. It is basically similar to the apparatus first used to find the antineutron by Cork, Lambertson, Piccioni and Wenzel. So far antineutrons have been produced, or, I should say, produced and observed only in charge-exchange reactions such as $\bar{p} + p \longrightarrow \bar{n} + n$. The antiproton beam from our spectrograph is incident from the left. y is a water Cerenkov counter in which various materials can be inserted. The large structure at the right is a 2' x 2' x 2' counter made up of alternate layers of lead and plastic scintillator. An antineutron event is identified by a large pulse in the sandwich counter without pulses in S_4 and S_5 and without large pulses in the Cerenkov counter. The latter excludes those antiprotons which annihilate and cannot therefore make antineutrons, while the 1 1/2" lead converter is used to materialize high-energy photons. One expects a pulse height spectrum from the lead sandwich counter quite similar to that obtained with the anti-protons since the energy release is the same in the annihilation of antineutrons or of antiprotons. Fig. 3 shows the pulse height spectra obtained with protons, π^-, p- and for those events which we classify as antineutrons. The pulse height distribution is not quite the same for $\bar{n}$ as for $\bar{p}$ because the anti-neutrons do not always hit as close to the center of the counter as do the antiprotons. However, it does extend into the large pulse height region.

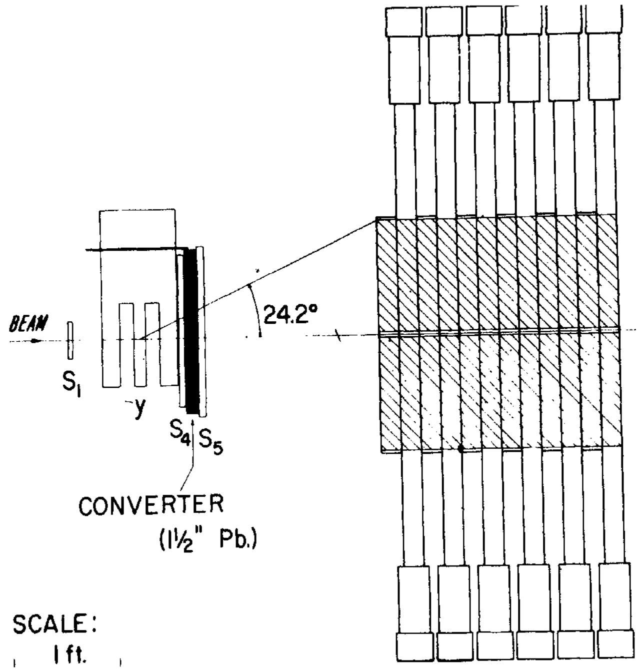

Fig. 2

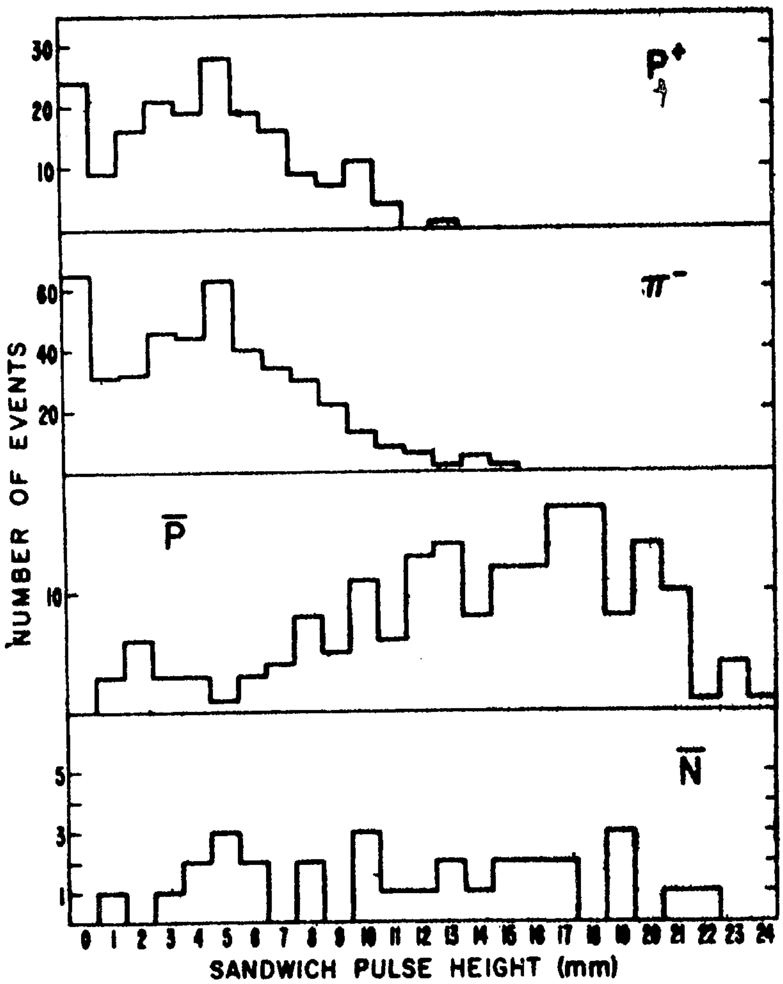

Fig. 3

I would like to speak now about the production cross sections of antinucleons. We have determined the differential production cross section for antiprotons by 6.2 Bev protons on copper. At 0^{o} and at an antiproton momentum of 1.19 Bev/c we find:

$$\frac{d^2\sigma}{d\Omega\ dp} \simeq 1 \times 10^{-30} \frac{\text{cm}^2}{(\text{sterad})\ (\text{Bev/c})} \quad \text{per nucleon in copper.}$$

This value is quite different from that given by Prof. Segre at the CERN symposium of last summer. Some of the change has arisen from corrections for the large nuclear absorption cross section for $\bar{p}$, from better estimates for the effective size of some of our magnetic lenses, but there was also an error in our previous computation. Our magnetic spectrograph consists really of two spectrographs in series. Because of the large number of stops involved the effective solid angle is not easy to calculate. We did this incorrectly before but I think we have now done it correctly. The value of the cross section is actually in fair agreement with the prediction of the Fermi statistical model, in fact, I believe the experimental value is a little larger than the theoretical value but it is certainly of the same order of magnitude. Something is known also about the variation of the yield with the momentum of the observed antiprotons (at fixed proton energy) from some work of Cork, Lambertson, Piccioni, and Wenzel. The values are:

Antiproton Momentum	$\frac{d^2\sigma}{d\Omega\ dp}$	
0.75 Bev/c	0.1×10^{-30}	
0.9	0.3×10^{-30}	$\frac{\text{cm}^2}{(\text{sterad})\ (\text{Bev/c})}$ per Cu nucleon
1.15	1×10^{-30}	
1.41	3×10^{-30}	

These values should be taken as no more than rough but perhaps realistic estimates. Perhaps Prof. Piccioni will discuss this point in more detail than I have. If one makes a statistical model calculation of the yield of antiprotons by 6.2 Bev protons on hydrogen. on the one hand, and on carbon, on the other, one concludes that a nucleon in carbon should be about 8 times as effective as a free nucleon because of the Fermi momentum of the nucleons in carbon. This factor is not so large as to discourage one completely from looking for the production of antiprotons in proton-proton collisions. We believe we have observed the production from hydrogen by using targets in the Bevatron of both CH_2 and carbon. The ratio of antiproton yield from a hydrogen nucleus to that from a carbon nucleus was 0.11 ± 0.06. Multiplying this by the number of nucleons in carbon we get a ratio of 1.3 ± 0.7 for the yield from free protons relative to that from a nucleon in the carbon nucleus. This is surprisingly large, since we had predicted that this ratio should be 1/8. The discrepancy is, at least in part, due to a large reabsorption in the carbon nucleus which was neglected in the original estimates. Still there is no getting around the fact that this yield is surprisingly high, and I think we will have to do considerable work in the not too distant future to recheck this measurement and to make quite sure of the absolute cross sections.

I have no new information on the excitation function, that is, the yield of antiprotons as the bombarding proton energy is varied and I'll say nothing about that. There is only the very crude excitation function of some years ago.

Let me talk about the production of antineutrons by charge exchange of protons. We had 497 Mev antiprotons incident on carbon, CH_2 , and lead. The apparatus used was that shown in Fig. 2, except that in the case of lead most measurements were done with the Cerenkov counter replaced by a solid layer of lead. The results obtained were:

Target	No. of events	σ	
Lead	1	$3.7^{+4.1}_{-2.6}$	mb/nucleus
Carbon	6	3.8 ± 1.5	mb/nucleus
CH_2	15	11.5 ± 3	mb/CH_2 molecule
Hydrogen (by difference)		3.8 ± 2.2	mb

The cross section refers of course only to antineutrons produced in a forward cone of half-aperture 17° . The results seem to indicate that a proton is about as effective as a carbon or lead nucleus.

I wish now to discuss the interaction cross section of antiprotons. The apparatus used is shown in Fig. 4. y is again a Cerenkov counter to detect annihilation processes. In addition the counters S_2 and S_3 serve for transmission measurements. The attentuation cross sections measured include scattering through angles larger than 14° (or 20°). The results are shown in Table 2, which includes measurements with positive protons. The ratio of anti-proton to proton cross section decreases with atomic number from oxygen to silver. It should be even smaller in lead. As a matter of fact, the measured lead cross section is suspiciously large, indicating some likelihood of difficulty with multiple scattering in this measurement. I had to omit the measurements at 14° because they showed very obviously the effect of multiple

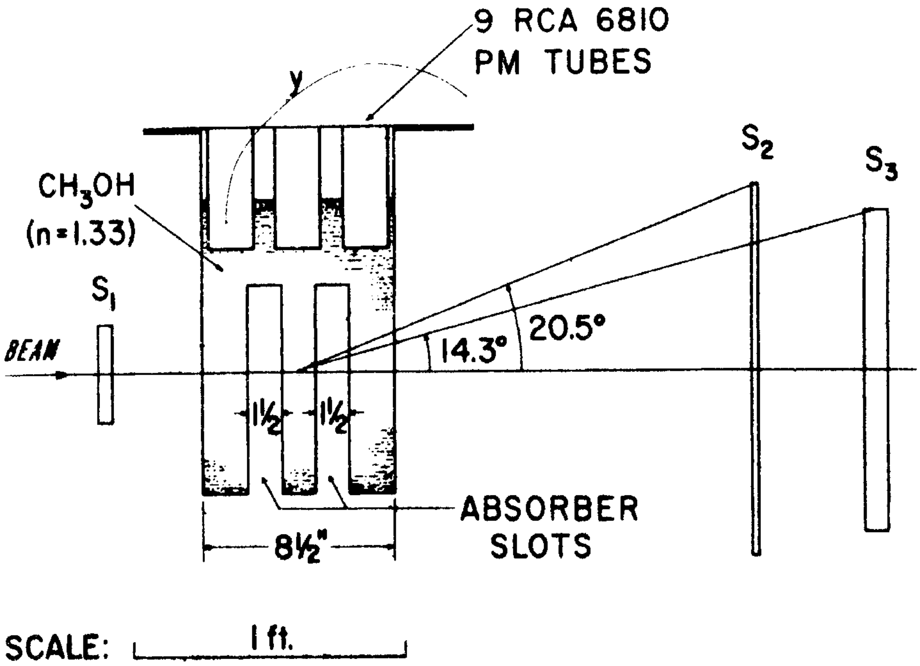

Fig. 4

Table 2

Antiproton and proton cross sections on various elements

	Energy (Mev)	14° cutoff $\bar{p}$	14° cutoff p	20° cutoff $\bar{p}$	20° cutoff p	Annihilation Cross section $\bar{p}$
Oxygen	457	556 ± 10	292 ± 2	517 ± 10	246 ± 2	453 ± 9
Copper	411	1240 ± 82	719 ± 5	1220 ± 88	640 ± 4	1040 ± 61
Silver	431	1630 ± 170	1052 ± 6	1640 ± 183	924 ± 6	1500 ± 157
Lead	463			2680 ± 254	1461 ± 10	2010 ± 182

scattering and that throws doubt on the results in lead with the 20^{o} cut-off angle as well. Table 3 shows some results of Cork, Lambertson,

Table 3

Antiproton cross sections

	K.E. (Mev)	Kind	Cross section (mb)
Carbon	700	25^{o}	436 ± 19
		total	657 ± 79
	300	inelastic	568 ± 102
		total	655 ± 130
Beryllium	500	2.6^{o}	460
		total	484 ± 60
	700	3.7^{o}	367
		1.9^{o}	416
		total	425 ± 50

Piccioni and Wenzel. The measured cross sections for carbon at 300 Mev (lower than in our work) seem to show a surprisingly small amount of elastic scattering in the forward direction. I think our first reaction when the annihilation cross section turned out to be so large was that nuclei must appear to antiprotons as black discs. If so, the forward scattering cross section should be equal to the absorption cross section. Apparently this is not a very good model since there is not much forward scattering.

We also have some measurements for the interaction of

452 Mev antiprotons on hydrogen. These were done by water-liquid oxygen difference with the apparatus shown in Fig. 5. The liquid in either case is used as a Cerenkov radiator to detect annihilations. Measurements with D_2O were also made to get the $\bar{p}$-n cross section by D_2O - H_2O difference. The results are given in Table 4, where the errors quoted are only the statistical errors. Realistic overall errors have not yet been estimated. The measurement of σ_{pn} at 20^o cutoff gave a result which differs by 7 mb from the accepted value. The origin of this discrepancy is not known. The results in the third line give the estimate of the $\bar{p}$-n cross section after applying the Glauber correction. This correction takes into account the hiding of one nucleon behind the other in deuterium. I think when we started this experiment we didn't realize how large the Glauber correction would be. It is already 5 or 10% for scattering of protons on deuterium. Since the antiproton has a cross section several times - let us say four times - larger, the Glauber correction becomes four times as large. This correction we have endeavored to make with an important assist from John Blair from the University of Washington and Dr. Henley will report on this method later. According to our corrected results the $\bar{p}$ p and $\bar{p}$ n cross section are not very different. Our data both for total and annihilation cross sections are certainly compatible with identical values for proton and neutron. If I subtract our result for σ ($\bar{p}$ p) with a 14^o cutoff from the total cross section given by the work of Cork, Lambertson, Piccioni and Wenzel this leaves a cross section of -6 ± 10 mb for scattering at angles less than 14^o.

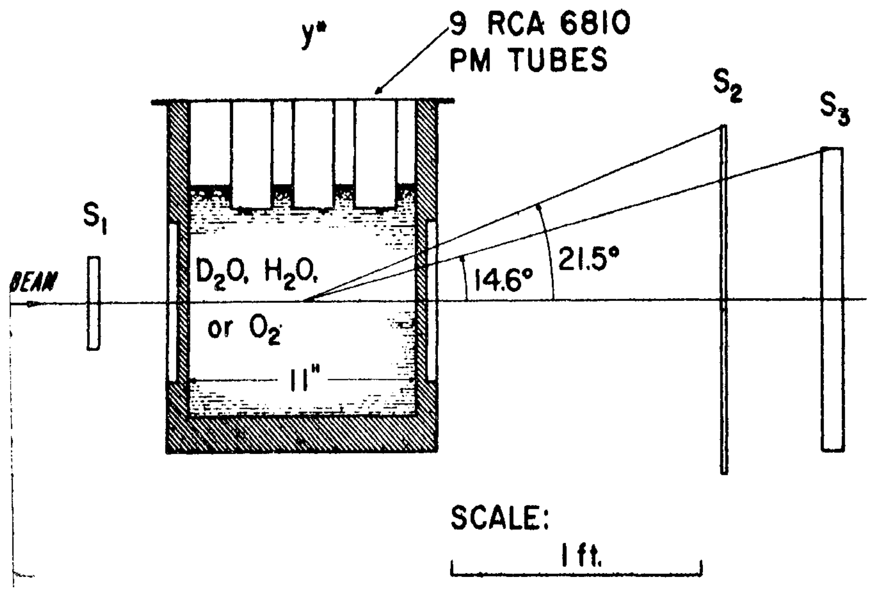

Fig. 5

Table 4

Antiproton and proton cross sections on protons and neutrons

Target	14° Cutoff Cross section		20° Cutoff Cross section		Annihilation Cross section	Total Cross Section
	$\bar{p}$	p	$\bar{p}$	p	$\bar{p}$	p
Proton	105±8 mb	25.1±1.2	104±8	24.4±1.3	39±7	99±7 (a)
"Neutron"(b)	70±8	28.7±1.1	70±8	-	46±8	
Neutron with shadow correction	112	31.6	112	-	74	

(a) From liquid hydrogen data of Cork, Lambertson, Piccioni and Wenzel.
(b) By subtraction of proton cross section from deuteron cross section.

There certainly has to be some elastic scattering in the forward direction. If one accepts both measurements, which I am inclined to do at the moment, I think they indicate that the forward scattering is probably relatively small, just as for carbon (but I presume it is not negative). Some forward scattering is guaranteed by the optical theorem but it does not have to extend over a very wide range of angles in the forward direction. We don't know quite what to do with this. It is a bit of a puzzle.

I would like to discuss next whether one can explain the cross section of nuclei using the elementary cross sections for antiproton on proton and antiproton on neutron. One attempt in this direction has been made by Gerson Goldhaber. He calculated

$$\sigma_{\text{nucleus}} = 2\pi \int_0^\infty \left[1 - e^{-\int \sigma_0 \rho \, dx}\right] b\,db$$

where b is the impact parameter and the nuclear density ρ has been taken from the Saxon potential as:

$$\rho(r) = \rho_0 / (1 + e^{\frac{r-R}{2}}) \qquad \text{with } R = 1.33\, A^{1/3}$$

(r and R in units of 10^{-13}cm.)

σ_0 is the average total cross section for p and n. The results shown in Fig. 6 indicate reasonable agreement with the data. One does not see any great discrepancy here between the observed cross sections for heavy elements and those expected from an optical model calculation. Dr. Drell will report on another optical model calculation.

I shall now discuss some of the results of the photographic emulsion work done at Berkeley in collaboration with the group at Rome. Fig. 7 shows the method of exposure. I

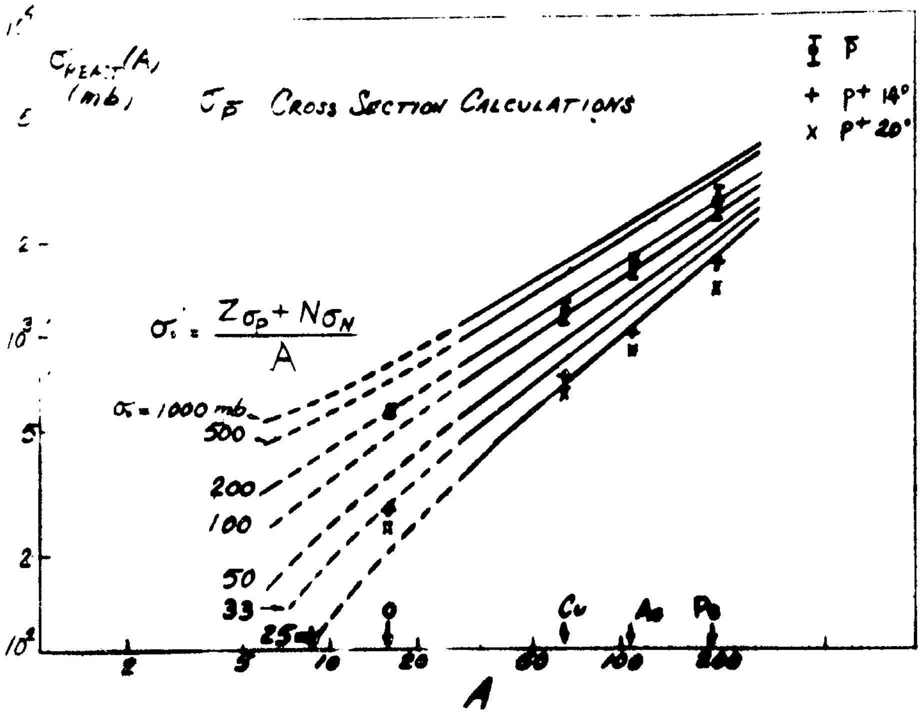

Fig. 6

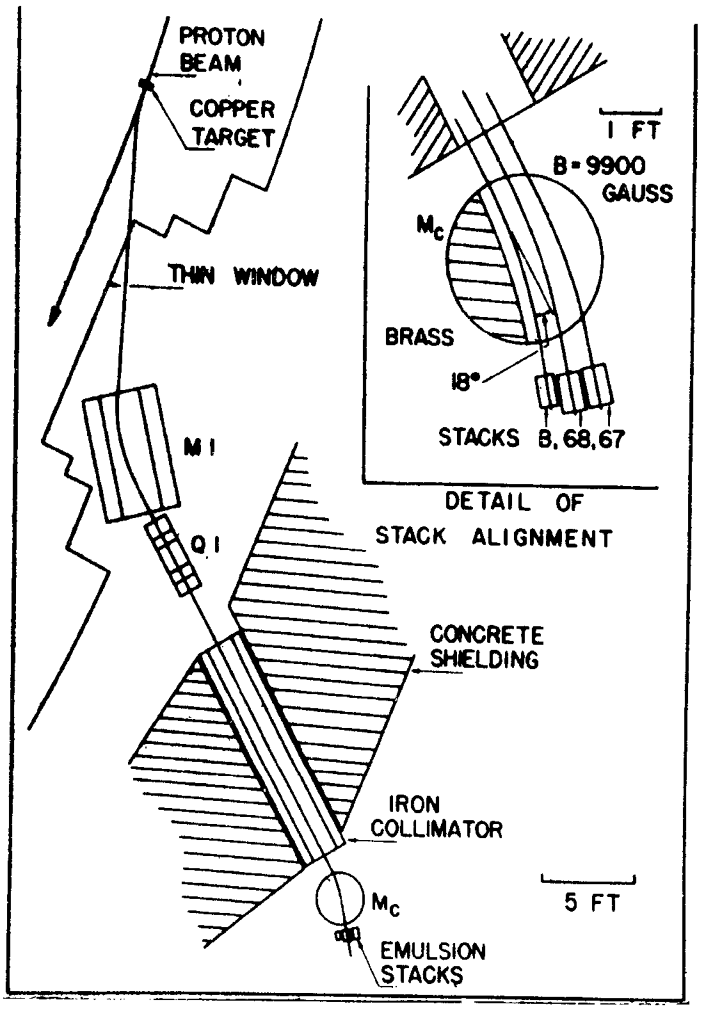

Fig. 7

would like to call attention in particular to the bending magnet M_c. It allows an unequivocal distinction to be made between positive and negative particles on the basis of their direction of entrance in the stack.

Table 5

Emulsion data on antiprotons

Number of stars	35
O-prong stops	2 (a)
Annihilations at rest	14
Annihilations in flight	21
Mean free path in emulsion	12.5 ± 2.8 cm
Annihilation m.f.p.	14.3 ± 3.4 cm
σ (ann.)/ σ (geometrical)	2.6 ± 0.6 (b)
σ (total)/ σ (geometrical)	2.9 ± 0.7
Average number of pions	5.3 ± 0.4 (c)
Average pion kinetic energy (d)	182 Mev
Same, corrected for nuclear excitation	206 Mev

(a) Excluded from analysis of annihilation process
(b) Based on geometric cross section: πr^2 with $r = A^{1/3} \times 1.2 . 10^{-13}$cm
(c) The observed number of charged pions is 2.6. We add 0.3 charged pions estimated to have escaped detection, 1.45 π^0's and an estimated 1.0 π reabsorbed in nucleus: $2.6 + 0.3 + 1.4 + 1.0 = 5.3$.
(d) A lower limit only can be given because the energy of some fast pions could not be measured.

Fig. 8 shows the visible energy release in the 35 stars (as a fraction of 2 $M_p c^2$). Clearly the two O-prong events could fit nicely at the tail of the distribution. Fig. 9 shows the charged pion number distribution

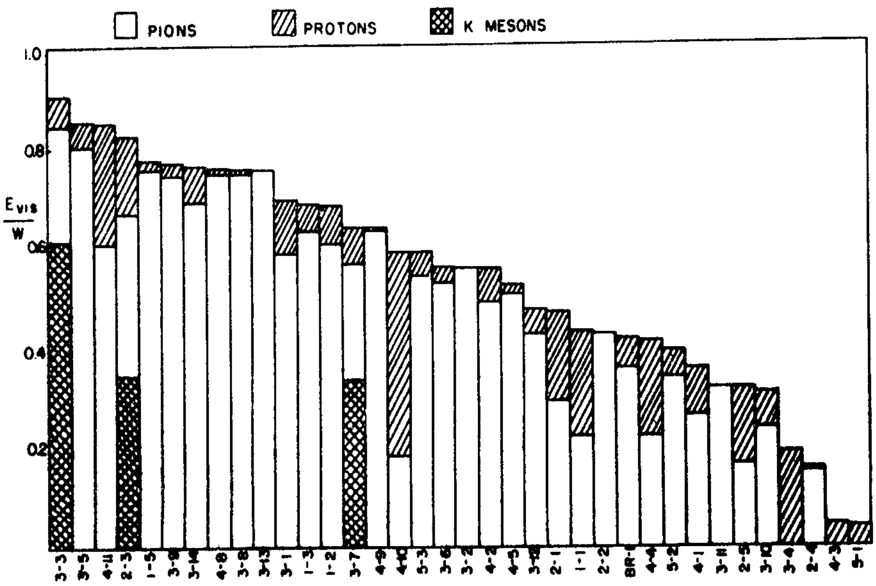

Fig. 8

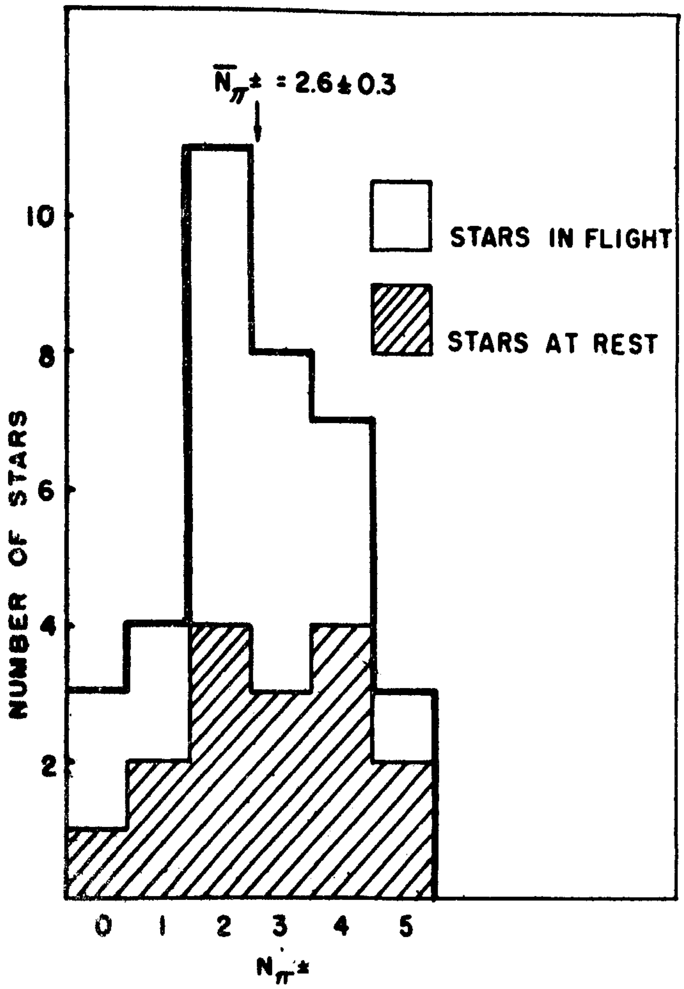

Fig. 9

in the same stars. An attempt has been made to compare calculations based on the Fermi model with these data and I think one should say that the statistical calculation simply does not give the right answer. In order to pull the experimental results into agreement with the statistical calculation one has to use a volume twelve times larger than the volume chosen by Fermi. I think this is an unreasonable stretching of the parameters and one should really say that the statistical analysis does not agree with these events. The difficulty of course is that the observed pion multiplicities are much too high.

Recently attempts have been made at Berkeley to obtain partially separated antiproton beams. The first attempt was made by placing some 20 g/cm^2 of lithium hydride at the first focus (F_1) of the spectrograph of Fig. 1, with the counters then replaced by the emulsion stack (preceded by a steering magnet as in Fig. 7). A 6" separation between mesons and antiprotons at the stack was expected. The exposure was fairly successful since the ratio of antiprotons to background had been improved by a factor of about 10, so that one could get about 10 times as many antiprotons in one stack before the emulsion was overloaded with minimum ionizing tracks. Goldhaber and Jauneau have found some 90 antiproton stars in one stack which is quite a lot. The contamination of pions was greatly reduced; the final background consisted of 4% π^- , 40% μ^- and 56% electrons. I should mention also that Cork and Wenzel in Berkeley are working on an electrostatic separation scheme which I would say at the moment looks very promising.

Finally I would like to comment briefly on the attempts that have been made to explain the large annihilation cross sections. A possible model just makes use of an absorptive core to represent the annihilation process. This model has been used by Koba and Takeda who got a scattering cross section of 33 millibarns and an annihilation cross section of 61 millibarns. To get this result, they had to use a radius for this absorptive region of $2/3\ \hbar/m_\pi c$ which seems rather inconsistent with the nucleon structure we heard discussed earlier. They point out that according to meson theory for antinucleon and nucleon the second order potential should be of opposite sign to the nucleon-nucleon potential. The fourth order potential should be of the same sign. Chew has suggested that one should try to use the potential discussed by Marshak and also by Thaler and Gammel together with an absorptive region that would correspond to the annihilation process. This has not been tried yet, but it seems to be a very natural suggestion.

DISCUSSION

SACHS: Does the visible energy release (Fig. 8) include the rest energy of the other (unseen) K-particle in those stars where one K-particle is seen?

CHAMBERLAIN: The mass of the invisible K meson has not been added, since K mesons could presumably be reabsorbed in the nucleus forming a hyperon.

FELD: Could you give an estimate of the ratio of K-particles to pions in annihilations?

CHAMBERLAIN: The observed K-mesons divided by the total number of π's (charged and neutral) is - I believe - 2%. Presumably the actual K's produced are about twice this because half the K-particles should be neutral. Also I believe there may be some additional prongs which could be K-particles, but which could not be identified as such.

PICCIONI: Experiments on antiproton interactions.

The research I am reporting is the work of B. Cork, G. L.

Lambertson, W. Wenzel, and myself at the Radiation Laboratory, Berkeley. The experiment was performed before the construction of the 8" diameter focusing lenses, thus exclusively 4" diameter lenses were used. Five such lenses formed the magnetic channel with magnetic fields so adjusted that each lens was making the image of the preceding lens on the following one. Two simple, but large, deflecting magnets determined the momentum of the particles. The accepted interval was close to $\pm$ 5% at all energies. Six scintillators arranged in two circuits of triple coincidences were placed along the magnetic channel (Fig. 10).

The time of flight of the particles along the 70 foot path determined the mass, as shown by the resolution curve of

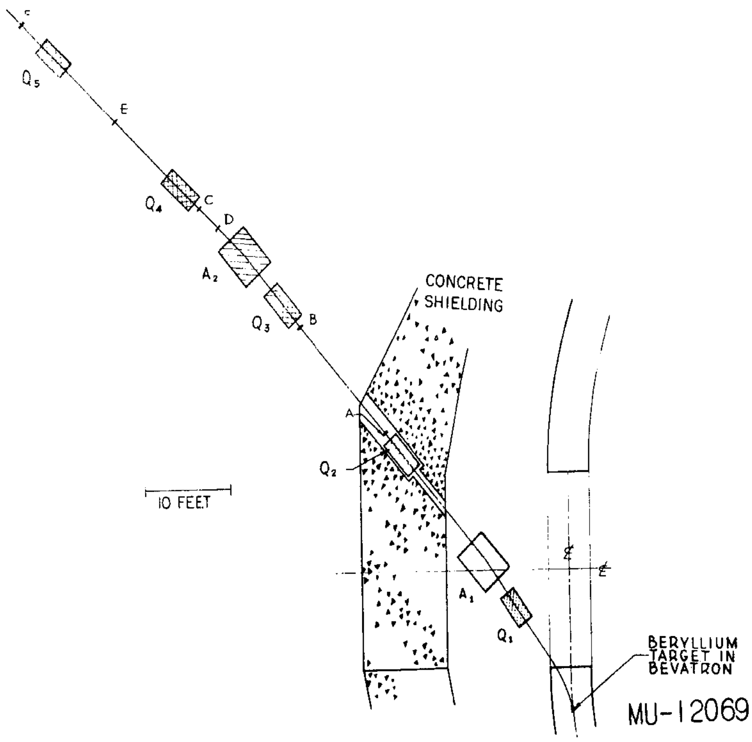

Fig. 10

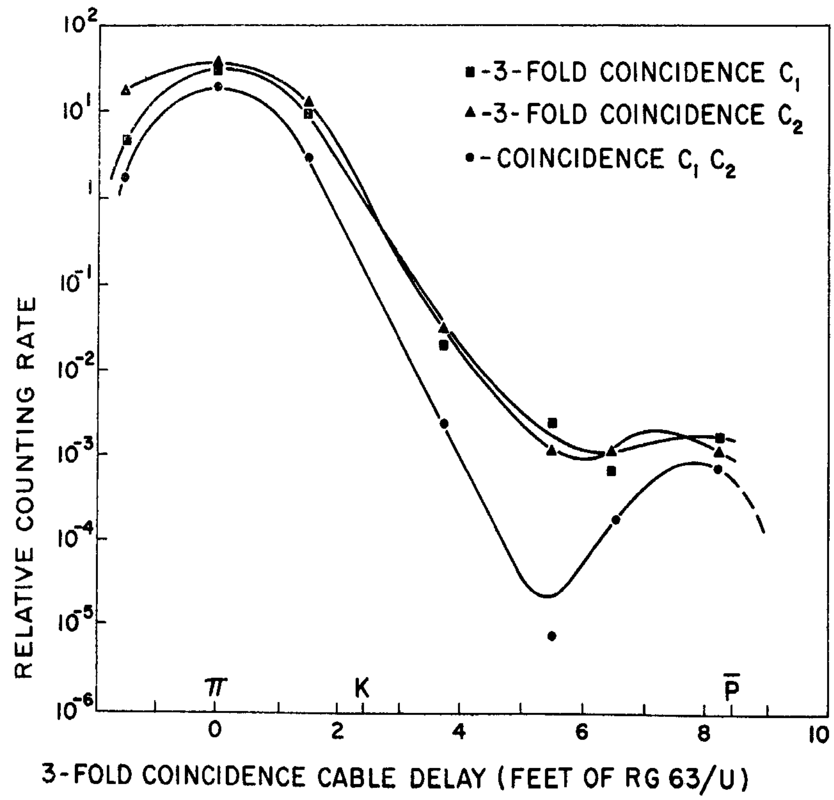

Fig. 11

Fig. 11, where the counting rate is plotted versus the delay, which is the parameter that determines the mass best detected by the apparatus. The curve also shows that the contamination in the antiproton counts is not more than a few percent. Such curves were repeated often during the measurements; observations with a Cerenkov counter were also made at times and confirmed the identification of antiprotons.

While the curve of Fig. 11 was obtained at 1.42 BeV/c momentum, Fig. 12 shows the curve obtained at .9 BeV/c. Here the detection of negative K-particles was possible, despite the large probability of decay between the source of such particles and the last of our counters. A measurement of the mean life of negative Kaons was possible by measuring the decay rate between the two last counters with the result $\tau = 1.5 \pm 2.5 \times 10^{-8}$ sec. in good agreement with the number previously reported by Alvarez at this conference. With the same hydrogen target which was used for the antiproton measurement, the total cross section of negative K's with protons was found to be 52 $\pm$ 9 mb.

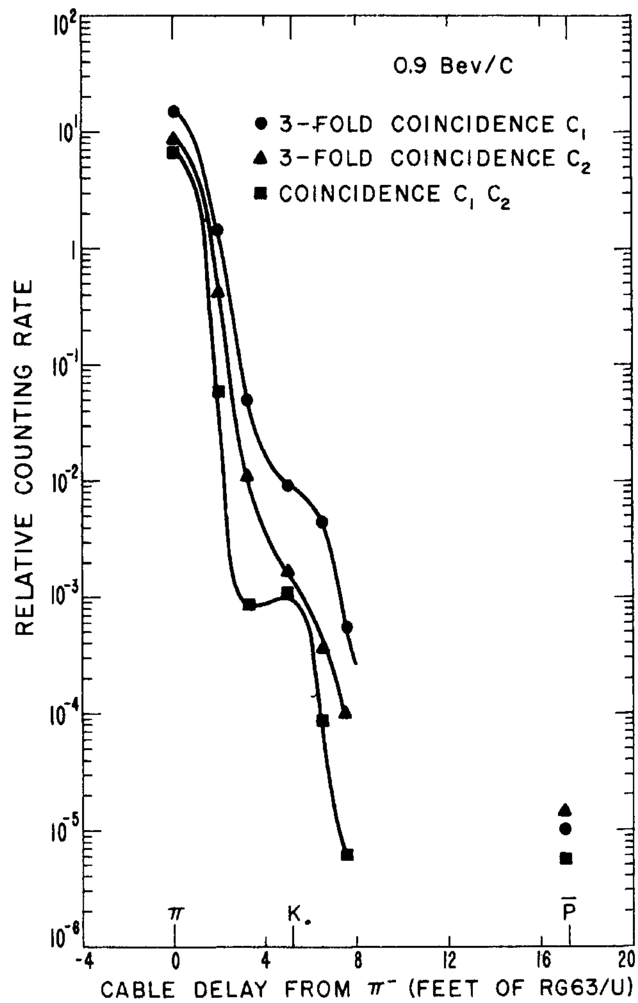

Fig. 12

For the measurement of the antiproton-proton total cross section the geometry of Fig. 13 was used.

The cone subtended by the last counter behind the hydrogen, had a semiaperture of 3.5 degrees. An approximate correction for this blind cone, calculated from the optical theorem

$$\sigma_{tot} = 4\pi \bar{\lambda}\, \mathrm{Im}\, f^0 ;\ \left(\frac{d\sigma}{d\Omega}\right)_0 = |\mathrm{Im}\, f^0|^2$$

was only about 2 millibarns.

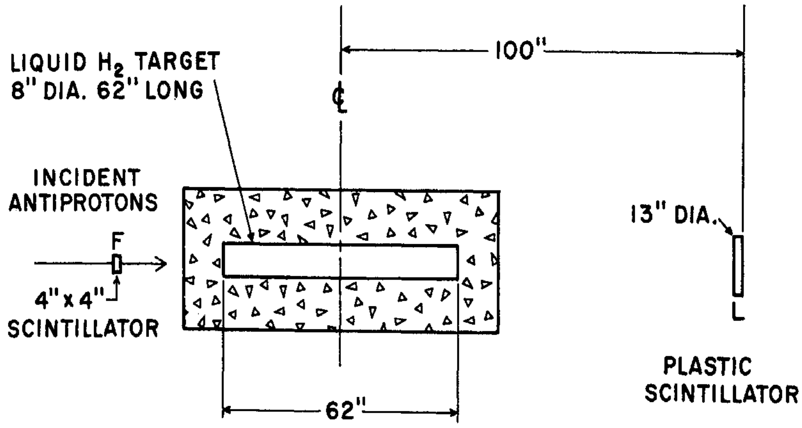

Fig. 13

The results are plotted in Fig. 14 where the p-p and n-p total cross sections are also shown for comparison.

The large value of the antiproton-proton cross section appears to be a salient feature of antiproton-proton interaction, and the energy dependence shown by our curve makes one think that very probably the total cross section will remain high at energies larger than 700 MeV.

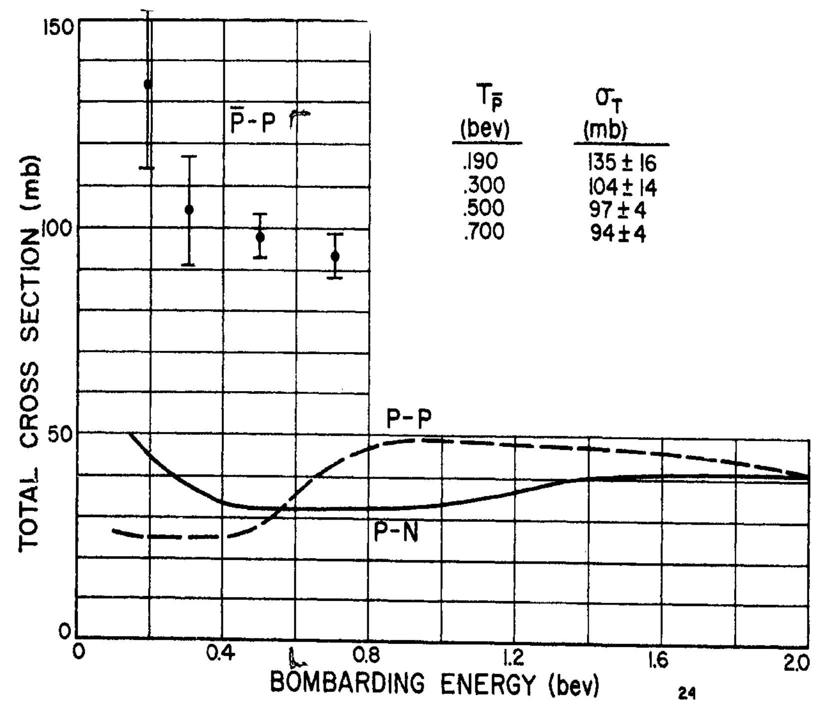

Fig. 14

Working with the same antiproton beam we have also measured the total cross sections of some nuclei. Using a scintillating liquid, viewed by photomultipliers, as an absorber it was possible to measure the interaction cross section of carbon (the very preponderant element in the liquid). The following table gives the data obtained with this method.

		Total (mb)	Inelastic (mb)
700 MeV	C	657 ± 79	436 ± 19
	Be	425 ± 50	
300 MeV	C	655 ± 130	568 ± 100

The elastic cross section of carbon therefore seems to be not more than 220 ± 80 mb, which would indicate that the carbon element, even though offering a large cross section to antiprotons, is by no means everywhere 100% opaque to such particles. A comparison between the recent data of Chamberlain et al. (inelastic cross section of antiprotons = 89 ± 7) and our value for the total cross section seems to point to a very similar situation for the elementary antiproton-proton collision.

DISCUSSION

GELL-MANN: Does anyone have any plan - in the case of the high-energy anti-protons - for looking for $\bar{p} + p \rightarrow Y + \bar{Y}$, or is this too hard an experiment?

PICCIONI: I don't know.

EKSPONG: Report on combined antiproton data.

The report is made on behalf of the following groups:

1. Antiproton Collaboration, Phys. Rev. 105; 1035 (1957)
2. W. W. Chupp (Berkeley)
3. H. Heckman, Smith (Berkeley)
4. G. Goldhaber, Jauneau (Berkeley)
5. J. Sandweiss (Berkeley)
6. E. Amaldi, Castagnoli, Ferroluzzi, Franzinetti, and Manfredini (Rome)
7. G. Ekspong, Johansson, and Rønne (Uppsala)
8. G. Frye, Rosen (Los Alamos)
9. O. Chamberlain, G. Goldhaber, Jauneau, Kalogeropolous, Segre, and Silberberg (Berkeley)

The data from groups 1 to 8 have been obtained in an experiment at the Bevatron identical with the one described in the collaboration paper; the last one is an experiment with a partly separated beam, in which the ratio of antiproton flux to background flux has been increased by a factor of 10 as compared to the earlier experiment. Some details about the separated beam were given by O. Chamberlain.

The situation as to the amount of information about antiprotons collected by emulsion work is the following; at last year's Rochester Conference only a handful of antiproton stars were reported; in the collaboration paper, data on 35 events were given; in this report there are data on 233 antiprotons. The distribution of the events among the research groups is detailed in Table 6.

Table 6

Antiproton events reported by various groups

Group	Total number of $\bar{p}$	Annihilations		Scatterings			Path length cm, 20-230 Mev	Stars Analyzed
		in flight	At rest	$\bar{p}$-p	Inel	Elast $\theta > 30^o$ $T > 30$ Mev		
1	35	21	14	-	1+(1)	1	287.7	35
2	5	1	4	-	-	-	49.4	(a)
3	26	12	14	-	-	-	280.6	16
4	15	7	8	1	-	-	139.7	(a)
5	25	17	8	-	-	-	179.7	(a)
6	14	10	4	-	-	-	102.9	14
7	8	5	3	1	-	-	86.9	8
8	15	(a)	(a)	(a)	(a)	(a)	(a)	(a)
9	90	41	49	3	-	1	766.2	(a)
Total	233	114	104	5	1+(1)	2	1893	73

(a) Analysis incomplete

The mass of the antiprotons. The following tables, given by the Rome group, (Tables 7 and 8) show the mass of the particles in units of the proton mass. Several methods have been applied and the results

Table 7

Mass measurements of antiprotons annihilating at rest (a)

Event	Total Range	R-p	R-β	R-pβ	$\langle a \rangle$ -R	π/π^{o}-R	Average
4	12.60	1.00 $\pm$.03	1.10 $\pm$.08	-	0.93 $\pm$.07	1.12 $\pm$.10	1.03 $\pm$.04
5	10.63	1.05 $\pm$.06	0.95 $\pm$.10	0.91 $\pm$.14	1.32 $\pm$.22	0.95 $\pm$.09	0.98 $\pm$.07
6	11.99	0.99 $\pm$.06	1.08 $\pm$.08	1.03 $\pm$.16	1.00 $\pm$.15	1.09 $\pm$.20	1.02 $\pm$.06
7	12.01	0.99 $\pm$.05	1.08 $\pm$.08	1.05 $\pm$.16	-	1.18 $\pm$.10	1.11 $\pm$.06
	47.23 cm	1.00 $\pm$.02	1.06 $\pm$.04	0.98 $\pm$.09	0.98 $\pm$.06		1.04 $\pm$.03

Table 8

Mass measurements of antiprotons annihilating in flight (a)

Event	Observ. range	p-β	β-pβ	Δi-ΔR	Average
8	5.90	1.07$\pm$.05	1.23$\pm$.12	1.10$\pm$.08	1.09$\pm$.04
9	11.03	0.89$\pm$.05	0.86$\pm$.07	1.07$\pm$.15	0.89$\pm$.04
10	8.05	1.06$\pm$.05	0.98$\pm$.09	1.16$\pm$.09	1.07$\pm$.04
11	4.29	1.14$\pm$.05	1.22$\pm$.13	0.90$\pm$.07	1.07$\pm$.04
12	5.29	1.12$\pm$.05			1.12$\pm$.05
13	5.96	1.09$\pm$.05	0.92$\pm$.08	1.07$\pm$.05	1.05$\pm$.03
14	4.90	1.00$\pm$.04	1.12$\pm$.11	1.58$\pm$.40	1.02$\pm$.04
15	4.15	1.12$\pm$.05	0.89$\pm$.09	1.39$\pm$.15	1.09$\pm$.04
16	5.92	1.01$\pm$.06	0.89$\pm$.14	0.93$\pm$.23	0.99$\pm$.05
17	0.95	1.01$\pm$.04			1.01$\pm$.04
	56.44	1.05$\pm$.01	0.97$\pm$.03	1.07$\pm$.03	1.04$\pm$.01

(a) The angle between any of the antiproton tracks listed and the pions at the point of entrance in the stack was less than 3^{o}

agree with protonic mass of the particles. It should be noted that the methods labeled R-p (range-momentum) for the stopping particles have been normalized to 1.00 in mass by a slight change of the momentum in the reference orbit from nominally 700 $\pm$ 4% MeV/c to 690 $\pm$ 7 MeV/c.

Annihilation cross section. From the data in Table 6 it is evident that out of 218 antiprotons 114 have annihilated in flight. The observed path length is 18.93 meters. There are among the tracks six which are labeled dubious events; the reason being that they cannot be proved to be due to antiprotons, because they interact in flight and release a visible energy which is less than the kinetic energy. If these particles are antiprotons (and they fulfill the rather stringent entrance criteria) one could expect some interactions at rest which give no (or almost no) visible energy. There are four such cases reported so far, which of course are difficult to distinguish from a possible background flux of positive protons. If we leave out all events of this type in computing the mean free path the systematic error left becomes probably insignificant. In doing so we have 108 annihilations in flight on an observed path length of 1859 cm in the energy region 20 - 230 MeV. The mean free path is then

$$\lambda_{\text{annih.}} = 17.2 \pm 1.7 \text{ cm} .$$

The error is the statistical error only (standard error). The systematic error is probably less than 0.5 cm. From this value of the mean free path we find for the cross section

$$\sigma_{\text{annih.}}/\sigma_o \quad 2.1 \pm 0.2$$

where σ_o has been computed for emulsion with a nuclear radius $R = 1.2\ A^{1/3} \times 10^{-13}$ cm. This value for the cross section has been obtained for antiprotons in the energy range 230 - 20 MeV, with a mean value at about 140 MeV.

$\bar{p}$-p scattering. There are five events which have been interpreted as elastic scattering on protons, see Table 6. A cross section for this process may be found from the known number of hydrogen atoms in the emulsion. The result is

$$(\sigma_{\bar{p}\,p})\ \text{scattering} = 85^{+57}_{-37} \text{ mb (5 events)}$$

Elastic scattering on nuclei. This seems to be a rare process. Only two events have been found with scattering angles $\theta > 30^o$ and with a kinetic energy $T_{\bar{p}} > 30$ MeV.

Inelastic scattering. Only one event is reported (in the $\bar{p}$ collaboration paper). In addition one non-definite event was also reported (the track left the stack before annihilating). No new event has been found. The cross section is $\lesssim$ 1% of the total cross section.

Small angle scattering. In the $\bar{p}$ collaboration paper data on about 1.6 meters of track length were reported. Now about 12 meters of antiproton track length have been examined for small angle scattering by the groups in Berkeley. About 4.5 meters of this comes from earlier exposures (Sandweiss) and about 7.5 meters from the separated beam exposure (G. Goldhaber). The method is described in the $\bar{p}$ collaboration paper. The results are shown in Fig. 15 together with a calculated curve based on a specific model, the "Charged Black Sphere Model" (Sandweiss). The agreement is good at higher angles but there is a lack of scatterings in the region 2^{o} - 6^{o}. Further work on the accuracy of the 2^{o} cutoff angle is in progress.

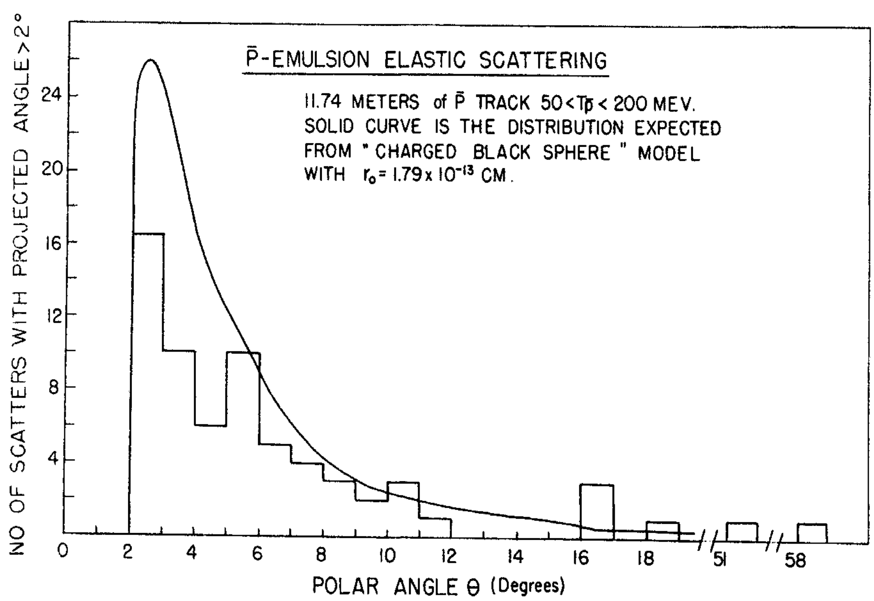

Fig. 15

The Annihilation Process

The pion multiplicity. By this we mean the "elementary" multiplicity in the annihilation with a nucleon. The observed multiplicity has to be corrected for the pions which get absorbed when the annihilation takes place at a nucleus. In the $\bar{p}$ collaboration it was found that on the average 1.0 pion gets absorbed in each process. There are some events where there is no visible nuclear excitation and where only pions are emitted. We begin by a study of the multiplicity for these events for which no absorption correction has to be applied. The events have the following charged pion multiplicities: 5, 5, 4, 4, 2, 2, 1 (7 events). The average charged pion multiplicity is 3.3. Including the neutral pions (multiplying by the factor 3/2) gives total average pion multiplicity $\simeq 4.9 \pm 1.0$.

Turning now to all analyzed stars (73 in number) we have seen 157 charged pions altogether. There is a correction to the number of annihilation stars which is -3 ± 3, for stars which might be due to charge exchange scattering of antiprotons or to a background flux of positive protons. There is also a correction to the number of observed pions which increases the number by $10\% \pm 7\%$ (This figure has been estimated by rechecking a sample of the stars). Thus we have an estimated number of $157 \times (1.1 \pm 0.07)$ pions in 70 ± 3 stars which give an average charged pion multiplicity of 2.46 ± 0.28. Including the neutral pions by multiplication with the factor 3/2 and adding the absorbed number of pions (1.0) we have finally a total average pion multiplicity of 4.7 ± 0.4. This figure agrees within statistics with the value 5.3 ± 0.6 given in the $\bar{p}$ collaboration paper and obtained by the same procedure.

K-mesons: there were four observed K-mesons in the $\bar{p}$ collaboration paper (and one possible hyperon). Two of the K-mesons were found in the same event. Now there are only two new K-mesons reported. Heckman and Smith have one for which the identification is based on the variation of ionization with range. This gives us 5 K-mesons in 70 ± 3 annihilation events. Among 15 stars G. Goldhaber and Jauneau have reported a definite case of a stopping K-meson, which was shown to decay in the $K_{\mu 2}$ - mode. (see Fig. 16). Thus there are 6 charged K-mesons observed in 85 ± 3 stars. The K/π -ratio is found to be:

$$\frac{\text{Number of charged K-mesons}}{\text{Number of pions (charged and neutral)}} = \frac{6}{400} \approx \frac{1}{67}$$

The fraction of events with charged K-meson emission is:

$$\frac{\text{Number of stars with charged K-meson emission}}{\text{Total number of stars}} = \frac{5}{85} \approx \frac{1}{17}$$

The energy of the charged pions. The kinetic energy distribution of 157 charged pions is shown in Fig. 17. To 29 out of 157 pions there has been given only a lower limit to the kinetic energy. This is because the track does not lend itself to accurate measurements due to a high angle of dip or to a short available path length etc. The lower limit to the kinetic energy in the majority of the 29 tracks is set at 140 MeV. We have treated them as follows: we have divided the 128 measured tracks in two groups, one consisting of 74 tracks with energies below 140 MeV and one group consisting of 54 tracks with energies above 140 MeV. Then it has been assumed that the 29 tracks with a lower

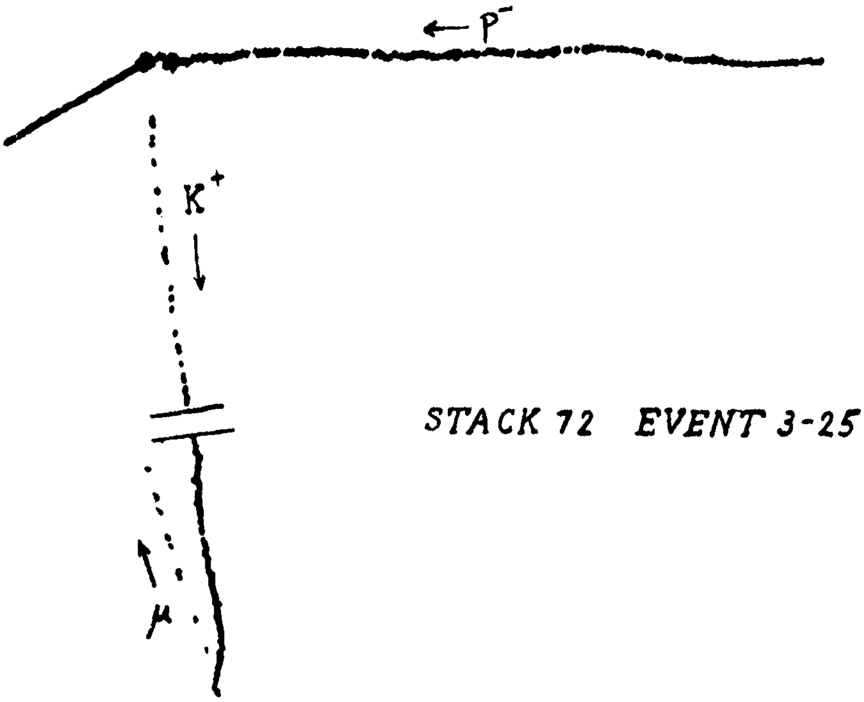

Fig. 16

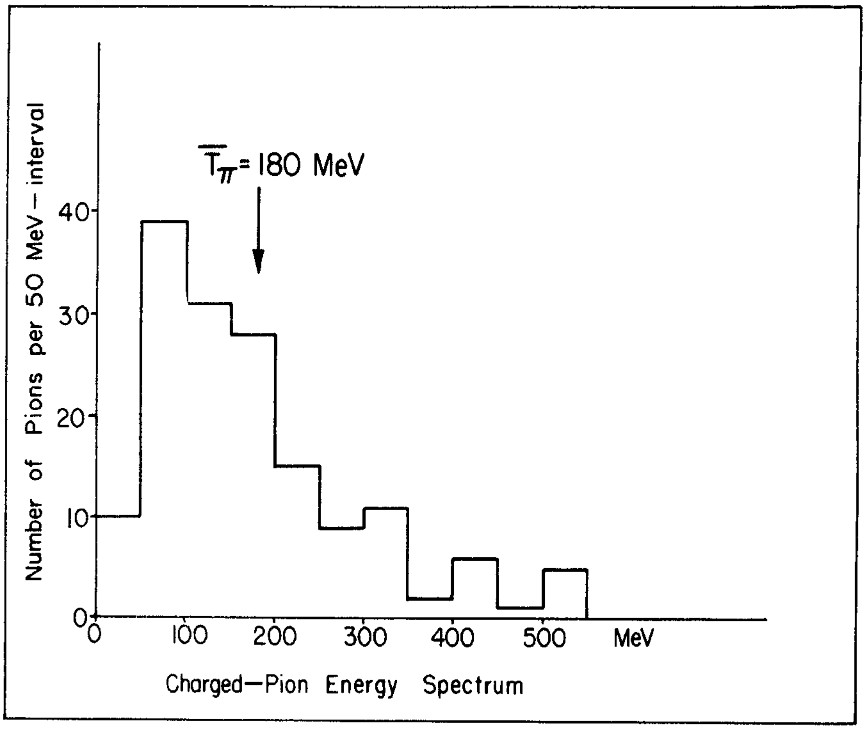

Fig. 17

limit given are distributed in energy in the same manner as are the measured tracks in the higher energy group. This procedure gives for the average pion kinetic energy $T_{\pi} = 180$ MeV. (This should be compared to the value given in the $\bar{p}$ collaboration paper, $T_{\pi} = 182$ MeV). This figure is somewhat lower than the average kinetic energy in the elementary process because some pions (0.3 per star) have been scattered by the nucleus and come out with a lower kinetic energy. Adopting a simplified version of the procedure in the $\bar{p}$ collaboration paper we find that the correction to the energy is

$$+23 \text{ MeV} = \frac{0.3}{2.24} \times (200 - 30).$$

The average pion kinetic energy in the elementary annihilation process is thus found to be close to 200 MeV. The new data thus confirms the conclusions made in the $\bar{p}$ collaboration paper.

Visible energy. About half of the stars (31 out of 73) show a visible energy release which is greater than $M_p c^2$.

Special events. The observation made in the $\bar{p}$ collaboration paper that stars with a large nuclear excitation were the result of annihilation in flight has been confirmed by the new data. The interpretation given is that the $\bar{p}$-nucleon annihilation at rest usually takes place at the surface of the nucleus - but that in flight some $\bar{p}$ may penetrate deep into nuclear matter releasing some 5 pions on the average. The energy of the pions is close to the big resonance (3/2, 3/2) so their mean free path in nuclear matter is much reduced. This model is consistent with the observation of some unusually large stars. As an example we may take a star (observed by the Uppsala group) caused by a $\bar{p}$ of 96 MeV kinetic energy in which one pion is emitted together with 15 heavy particles (mostly protons). Among these are 5 protons with high energy ("knock-on" protons): the energies ranging from 70 MeV to 275 MeV.

The first $\bar{p}$ event with an electron pair related to it has been observed by G. Frye, Los Alamos. The pair is interpreted as due to the decay of a π^0 into 2 γ with subsequent pair production of one of the γ rays. It should be noted that this is not a "Dalitz"-type pair. Preliminary measurements indicate an energy $>$ 100 MeV for the pair and shows that its origin is probably at the star; the distance from the center of the star to the plane defined by the pair tracks being $< 0.2\ \mu$. The event is the result of an annihilation in flight of a 110 MeV antiproton.

DISCUSSION

CHEW: This is certainly not an explanation (of the big cross section), but I just wanted to draw attention to a circumstance which must have been obvious to lots of people but which did not occur to me until a couple of days ago when I was listening to the nuclear force discussions. If you believe the picture that outside the core the only thing that counts very much is the π -meson cloud, then we should be able to say what the interaction outside the core region is between the nucleon and the antinucleon. If the nuclear forces are predominantly due to the exchange of one meson and two mesons then the one-meson exchange gives rise mainly to a tensor force, the two-meson exchange mainly to a central force. According to the theory the one-meson exchange would have the opposite sign for the nucleon-antinucleon combination and the two-meson exchange would have the same sign. So that a semi field-theoretical model which suggests itself is to take the two-nucleon force that we now have and change the sign of the tensor part, keep the same central part and replace the core by an absorptive region and just see what comes out. My intuition is nowhere near good enough to say what is going to happen, I think it is very complicated.

SALAM: As there seem to be no other comments I will try to recall some comments I heard from Lévy about three or four months back. He has the following picture for the force between the proton and the antiproton. He remarks that the pion multiplicity of 5.3 is roughly the total energy divided by the resonance energy in the p-wave scattering of pions. From this he deduces that the proton-antiproton force proceeds mainly through an exchange of a large number of pions whereas the proton-proton force and the neutron-proton force can be explained mainly by an exchange of one or two mesons at most. In this case where we have an antiparticle in the process the number of mesons which are exchanged is very much larger, and in fact the picture as he proposes is that annihilation takes place through a graph where most of the vertices correspond to p-wave interactions and there is just one vertex which corresponds with an s-state and which is responsible for the actual nucleon antinucleon annihilation process. He then makes the simple observation that with a large number of mesons the energy denominator can vanish. This gives him a large imaginary part and the large absorption. This is the picture which he has proposed.

CHEW: It seems to me that although this effect certainly is important, it would be represented only by a very short-range part of the interaction. I don't quite see why the five-meson exchange could reach out to distances of the order of a full meson Compton wavelength.

MARSHAK: One point which is connected with this high multiplicity: I would like again to emphasize how difficult it is to understand this 5.3 on the basis of the statistical model. The Berkeley group has been required to use something like 20 times the usual volume $\frac{4\pi}{3}\left(\frac{\hbar}{m_\pi c}\right)^3$ in order to get this high multiplicity. For example, we tried postulating the existence of nucleonium, a strongly bound state of nucleon and antinucleon, which could only decay into a minimum of four mesons, a state which Goebel and others have shown may exist on the basis of the G -invariance principle. But even so, it is just very hard to push up the multiplicity which you predict on the basis of the statistical model. You can reach 3.7 but to get to 5.3 is really very tough.

FULTON: I would just like to refer back to the discussion of Dr. Salam. At Hopkins we have been thinking along a similar line and we haven't really completed the calculation but the indications are that there are a large number of mesons in the intermediate state in the annihilation processes and that the cross sections tend to increase above what you would normally expect.

CHAMBERLAIN: I had meant to point out that the average kinetic energy of the pions emitted is remarkably close to the resonance energy. I suppose this is also a consequence of just the multiplicity but it is remarkable how even in the energy spectrum of the mesons the energy comes very close to the resonance and this may perhaps be tied in with the same explanation.

In answer to questions from the floor Matthews commented on the Levy model.

MATTHEWS: I think it's very hard to get anything quantitative out of this picture, because it does involve very complicated graphs. There doesn't seem to be any reason in this case to think that at long range the potential will be given at all well by the first and second order perturbation theory.

SALAM: This is just the opposite of what Chew has said.

HARA: A reformulation of pion-nucleon interactions.

The very large nucleon-antinucleon cross sections and the

Stanford experiments throw some doubt about the type of pion-nucleon interactions that have been used thus far. I will talk about an attempt to reformulate the interaction. The starting point is charge conjugation. In a recent paper (O. Hara and Y. Fujii, Prog. Theor. Physics 17 (1957), in press.) we proposed a scheme where the degree of freedom associated with the particle and antiparticle states is related to the third component of a vector $\underline{K}$. In this theory the electric charge of nucleons and antinucleons is given by:

$$Q = e\,(I_3 + K_3)$$

$$K_3 = 1/2 \text{ for nucleon} \qquad |K| = 1/2$$

$$= -1/2 \text{ for antinucleon}$$

I_3 and K_3 are the third components of the isotopic spin vector $\underline{I}$ and of the new vector $\underline{K}$.

The invariance of the theory under rotations in I-space constitutes charge independence. We assumed the π -nucleon interaction to be invariant also under rotations in K-space. Roughly speaking we go from nucleonic charge symmetry to nucleonic charge independence. If this is assumed the pion-nucleon interaction, and in particular the part responsible for the creation and annihilation of pairs, cannot be local. To show this, consider the usual form of pseudoscalar π -N interaction:

$$H = ig \sum \bar{\psi}(x)\,\gamma_5\,\tau_i\,\psi(x)\,\phi_i(x)$$

If $\bar{\psi}$ (x) and ψ (x) are expanded in a Fourier series, $\bar{\psi}\gamma_5\tau_i\psi$ becomes:

$$\psi\gamma_5\tau_i\psi = \frac{1}{2V}\sum\left\{\begin{array}{l} \bar{u}(k'\sigma')\gamma_5 u(k\sigma)\,\chi^*(k'\sigma')\begin{pmatrix}\tau_i & 0\\ 0 & -\tau_i\end{pmatrix}\chi(k,\sigma)\,e^{i(k-k')x} \\ +\,\bar{v}(k'\sigma')\gamma_5 v(k,\sigma)\,\chi'^*(k'\sigma')\begin{pmatrix}\tau_i & 0\\ 0 & -\tau_i\end{pmatrix}\chi'(k,\sigma)\,e^{-i(k-k')x} \\ +\,\bar{u}(k'\sigma')\gamma_5 v(k,\sigma)\,\chi^*(k'\sigma')\begin{pmatrix}\tau_i & 0\\ 0 & -\tau_i\end{pmatrix}\chi'(k,\sigma)\,e^{-i(k+k')x} \\ +\,\bar{v}(k'\sigma')\gamma_5 u(k,\sigma)\,\chi'^*(k'\sigma')\begin{pmatrix}\tau_i & 0\\ 0 & -\tau_i\end{pmatrix}\chi(k,\sigma)\,e^{i(k+k')x} \end{array}\right\}$$

where u(k,σ) and v(k, σ) are four solutions of the Dirac equation, and χ (k, σ) and χ' (k, σ) are given by

$$\chi(k,\sigma) = \begin{bmatrix} p\ (k,\sigma) \\ n\ (k,\sigma) \\ \bar{n}\ (k,\sigma) \\ -\bar{p}\ (k,\sigma) \end{bmatrix} \quad \text{and} \quad \chi'(k,\sigma) = \begin{bmatrix} \bar{p}^*\ (k,\sigma) \\ \bar{n}^*\ (k,\sigma) \\ n^*\ (k,\sigma) \\ p^*\ (k,\sigma) \end{bmatrix}$$

where p(n) and $\bar{p}(\bar{n})$ denote the creation and annihilation operators for proton(neutron) respectively.

In (1) terms like $\chi^*\begin{pmatrix} \tau_i & 0 \\ 0 & -\tau_i \end{pmatrix}$ can be written as $\chi^*\begin{pmatrix} \tau_i & 0 \\ 0 & \tau_i \end{pmatrix} K_3$

where K_3 is one of the Pauli matrices in the K-space. Therefore, this is not a scalar but the third component of a vector in the K-space. To make this invariant, it is necessary to replace K_3 by the unit matrix. If this modification is made, however, (1) vanishes. The minimum modification necessary to avoid this difficulty is to reverse the sign before the second term and to make the third and the fourth term non-local (Exactly the same situation also occurs in the case of the pseudovector interaction.) The form of the form factors appearing there is restricted by the condition of hermiticity, and the modified interaction Hamiltonian is given by:

$$\begin{aligned} H' = \frac{ig}{2V} \sum \Big\{ & \bar{u}\gamma_5 u\, \chi^*\begin{pmatrix} \tau_i & 0 \\ 0 & \tau_i \end{pmatrix} e^{i(k-k')x} + \\ & + \bar{v}\gamma_5 v\, \chi'^*\begin{pmatrix} \tau_i & 0 \\ 0 & \tau_i \end{pmatrix} e^{-i(k-k')x} + \\ & + \int f(x-y, x-z)\, dy\, dz \Big[\bar{u}\gamma_5 v\, \chi^*\begin{pmatrix} \tau_i & 0 \\ 0 & \tau_i \end{pmatrix} \chi' e^{-i(ky+k'z)} \\ & \qquad + \bar{v}\gamma_5 u\, \chi'^*\begin{pmatrix} \tau_i & 0 \\ 0 & \tau_i \end{pmatrix} \chi\, e^{i(ky+k'z)} \Big] \Big\} \phi_i(x) . \end{aligned}$$

Written in the form resembling the usual one as closely as possible, it is

$$H' = ig \sum \left\{ \begin{aligned} & \bar{\psi}^{(+)}(x)\gamma_5\tau_i\psi^{(+)}(x) - \bar{\psi}^{(-)}(x)\gamma_5\tau_i\psi^{(-)}(x) + \\ & + \int f(x-y, x-z)\, dy\, dz \left[\bar{\psi}^{(+)}(x)\gamma_5\tau_i\psi^{(-)}(y) - \bar{\psi}^{(-)}(z)\gamma_5\tau_i\psi^{(+)}(y) \right] \end{aligned} \right\} \phi_i$$

where $\psi^{(+)}(x)$ and $\psi^{(-)}(x)$ are positive and negative frequency parts of $\psi(x)$ respectively.

In addition to non-locality the other characteristic of this interaction is that the vertex responsible for the emission and the absorption of a pion by an antinucleon has the opposite sign compared to the ordinary one as the result of replacing K_3 by the unit matrix in (1). Therefore the nucleon-antinucleon potential resulting from the exchange of an odd number of pions has the opposite sign compared to the ordinary one.

It would clearly be desirable to check the validity of the theory by comparison with experiment. One test is provided by $\bar{N}$-N scattering since the theory gives a very simple relation between $\bar{N}$-N and N-N scattering. Another test is the annihilation process. Consider, for example, the system composed of a nucleon and an antinucleon. Its particle number is zero. According to our theory, however, there can be two states corresponding to K = 0 and 1 respectively. The former can annihilate into pions as usual, but for the latter this is impossible from the conservation law of K, and it can annihilate only by first emitting a γ -ray. (The selection rule for the γ -transition is given by $\Delta I = \pm 1, 0$; $\Delta I_3 = 0$, and $\Delta K = \pm 1, 0$; $\Delta K_3 = 0$, since the electromagnetic interaction is the third component of a vector in charge space.)

The fraction of the energy carried by the γ -ray is estimated to be about 40%. Since the states corresponding to K = 0 and 1 occur equally, the average percentage of the energy carried by the γ -ray becomes about 20%. This is considerably larger than would be expected from the usual theory.

DISCUSSION

CHAMBERLAIN: There is one thing I like very much about Dr. Hara's proposal. It makes a very definite prediction in the case of antiproton-proton scattering in that half of the states involved should imitate exactly the nucleon-nucleon scattering. This means that if we can show that there is very little antiproton-proton scattering compared to proton-proton scattering we would then disprove his theory.

DRELL: Optical model analysis of antiproton-nucleus interactions.

The optical model provides a well known connection between the inelastic cross section for a particle p incident on a nucleus A, the density distribution of the nuclear matter ρ , and the total interaction cross section of the incident particle with a nucleon, σ^t_{pN} :

$$\sigma^{in}_{pA} = 2\pi \int_0^\infty b\,db \left[1 - \exp\left(-\int ds\, \rho\, \sigma^{t}_{pN}\right)\right] , \qquad (1)$$

where b is the impact parameter of the particle and s the co-ordinate along its (assumed) straight line path. Fernbach, Serber, and Taylor, Phys. Rev. 75, 1352 (1949) . The simplicity of Eq. (1) lies in the fact that only the absorptivity of the nucleus appears and not the real part of the nuclear potential. Eq. (1) has provided satisfactory interpretations of experimental data in numerous applications to high-energy pion and nucleon inelastic nuclear cross sections.

We report here the application of Eq. (1) to the inelastic cross sections of antiprotons of K.E. = 400-450 Mev incident on O, Cu, Ag, and Pb as reported earlier in this session by Chamberlain. The aim of this calculation is simply to see if the observed cross sections are compatible with the simple optical model or if there are significant corrections due to polarization of the nuclear matter or due to deflection of the incident antiproton in a deep attractive nuclear potential as proposed by Duerr and Teller [Phys. Rev. 103, 469 (1956)] .

In order to avoid the question of the relative sizes of the neutron and proton distributions in ρ , we consider the ratio of antiproton to proton cross sections, which, to first order, depends only on the fall-off distance of ρ and not on its actual size. Taking for the fall-off distance of ρ the Hofstadter results for the charge density, [Rev. Mod. Phys. 28, 214 (1956)] , we obtain an approximate analytic formula for this ratio

$$R_{\bar{p}p} = \frac{\sigma^{in}_{\bar{p}A}}{\sigma^{in}_{pA}} = 1 + \frac{1.7}{A^{1/3}} \ln \left(\sigma^{t}_{\bar{p}N} / \sigma^{t}_{pN} \right) \qquad (2)$$

The physics in Eq. (2) is as follows: $R_{\bar{p}p} - 1$ measures, as a function of A and of elementary cross sections, the difference in impact parameters at which the nucleus provides a mean free path for absorption, i.e., makes the transition from opaque to transparent. The $1/A^{1/3}$ dependence expresses Hofstadter's results that the surface layer has a constant thickness independent of A. The logarithmic dependence on the elementary interaction cross section results because of the rapid decrease of ρ at the surface and the fact that it can be accurately fitted to a gaussian shape in the region in which ρ drops from one-half to one-tenth of its maximum value. This is the region of interest here since it contains the impact parameters for which the nucleus changes from opaque to transparent. The numerical constant results from averaging ρ in Eq. (1) over a region corresponding to the finite range of the elementary interaction (taken to be, for convenience, of gaussian shape with a half width of a pion compton-wave length).

Eq. (2) is intended then to provide a convenient analytic form for experimental comparison, with accuracy $\approx$ 10%. (A more detailed study suggests increasing the "constant" 1.7 by 5% for A $<$ 20 and decreasing it 3% for A $>$ 200).

In comparing Eq. (2) with experiment we note that $\sigma^t_{\bar{p}p} \simeq \sigma^t_{\bar{p}N} \simeq 105$ mb, as is deduced from the Berkeley measurements on $\sigma^t_{\bar{p}D}$ when the double scattering correction to the impulse approximation analysis is taken into account. (This double-scattering correction is equivalent to the shadow effect of Glauber (Phys. Rev. 100, 242, 1955)).

The comparison is as follows:

Element	Eq. 2	Chamberlain report
O	2.0	1.92 $\pm$ .03
Cu	1.6	1.70 $\pm$ .1
Ag	1.5	1.55 $\pm$ .15
Pb	1.4	1.85 $\pm$ .2

The observed agreement and trend (except in the questionable case of lead mentioned by Prof. Chamberlain) supports the validity of a simple optical model interpretation for the inelastic cross sections of antiprotons in nuclear matter. It sheds no light, however, on the question of the large magnitude of $\sigma^t_{\bar{p}N}$ itself.

DISCUSSION

GLAUBER: It may be worthwhile to point out that the optical model may require larger corrections in the case of antinucleons than in the case of the nucleons. The optical model is derived on the assumption that there is no correlation at all in the position of nucleons in a nucleus. As soon as there is a correlation then shadowing effects become important as they do in the deuteron. You can show for example that the Fermi correlation which keeps nucleons apart from one another, will actually increase the effective cross section of particles in a nucleus making it a trifle larger than the free nucleon cross section (as it enters the opacity formula). This is an effect which is proportional to the square of the cross section: the double scattering effect as in the deuteron. This will be more important in nuclei than it is in the deuteron.

GOEBEL: Optical model fitting of the elastic antiproton cross section.

This is a calculation similar to Dr. Drell's, except that we are especially interested in fitting the elastic cross section. Because this is so small, we shall at the start minimize it by assuming a purely absorptive $\bar{p}N$ interaction, i.e. a purely imaginary scattering amplitude. We neglect the thickness of the nucleus in the calculation of the elastic scattering. We use a Gaussian shape for the carbon nucleus, because then the calculation becomes completely analytical. The size we take from Hofstadter: $r_{rms} = 2.47 \times 10^{-13}$cm. The data we shall fit are the average of Piccioni's at 300 and 700 MeV; i.e. "at 500 MeV":

$$\sigma_{in} = 500 \text{ mb}, \ \sigma_{tot} = 655 \text{ mb, by subtraction } \sigma_{el.} = 155 \text{ mb.}$$

Let us first fit σ_{in} by choosing $\sigma_{\bar{p}N}$; we find $\sigma_{\bar{p}N} = 85$ mb (which fits well with the observed $\bar{p}N$ cross sections). This implies $\sigma_{el,\,\bar{p}C} = 205$ mb which is actually within the experimental error of Piccioni's measurements. However, let us take the experimental cross sections seriously, and fit both σ_{in} and the ratio $\sigma_{el}/\sigma_{in} = .31$ by giving the $\bar{p}N$ interaction a finite range. We take each nucleon to be seen by the $\bar{p}$ as a Gaussian shaped absorptive distribution. The fit is accomplished with $\sigma_{\bar{p}N} = 80$ mb and $(\text{"}r_{\bar{p}N}\text{"})_{rms} = 2.7 \times 10^{-13}$cm. (One should emphasize that these calculated numbers should not be taken any more seriously than the experimental numbers: they must be strongly dependent on the tails of the shape distributions. For instance, it is a peculiarity of the Gaussian distribution that $\sigma_{el} \lesssim 1/2\ \sigma_{in}$, compared to $\sigma_{el}/\lesssim \sigma_{in}$ for a uniform disk.) This size of the $\bar{p}$ is so large and therefore its transparency is so great, that the ratio $(\sigma_{el}/\sigma_{in})_{\bar{p}N}$ is extremely small: $\sigma_{el,\,\bar{p}N} \simeq 1$ mb. This is consistent with the measurements of Chamberlain and Piccioni, which at the moment state $\sigma_{el,\bar{p}p} < 0$! The $\bar{p}$-hydrogen scatterings reported by Ekspong in emulsion are "large angle" and have no bearing on the question of the absence of the $\bar{p}$ p diffraction peak; of course they do indicate (as does Chamberlain's measurement of $\sigma_{el, \bar{p}p, \text{ large angle}} \simeq 15$ mb) that the $\bar{p}N$ interaction is not purely absorptive, i. e. there is a real part to the scattering amplitude which will add to the $\bar{p}C$ elastic scattering.

The above "transparency" model of the $\bar{p}N$ interaction may have a bearing on the multiplicity problem, since it implies that a large proportion of annihilations take place in large angular momentum states. Perhaps emission of a few pions in large ℓ states is difficult compared to the emission of many pions, each in a small ℓ state.

DISCUSSION

BERNARDINI: In view of the large cross section of antiprotons, I wonder whether the production of nucleon antinucleon pairs would be affected by the strong interaction in the final state.

HENLEY: Calculation of the shadow effect in antiproton-deuteron scattering.

I would like to report very briefly on a calculation performed by Dr. Blair which takes into account the shadow effect in antiproton deuteron cross sections. Since the wavelength of the incoming antiproton is so short, you can use the impulse approximation. If you take the primary interaction between antiproton and proton and between antiproton and neutron to be represented by black absorbing discs of radii a and b say, then one can perform such a calculation and perform the correction rather simply. Of course the assumption of a black disc really becomes quite questionable after what we have heard, earlier this afternoon. The calculation is performed by first projecting the deuteron wave function on a plane at right angles to the beam. For the deuteron he used the Hulthen wave function:

$\dfrac{e^{-\alpha r} - e^{-\beta r}}{r}$, with $\beta = 7\alpha$. The results which Dr. Chamberlain presented earlier come out by integrating the projected area over the eclipsed area of the neutron and proton on the plane at right angles to the beam. The results which were presented earlier are that if the antiproton-proton cross section is 105 mb and the apparent antiproton neutron cross section is 70 mb the corrected area adds 42 mb to this, so one gets 112 mb for the true antiproton neutron cross section which is quite comparable to 105 mb for the antiproton proton cross section.