VII. Friday Afternoon: Anti-Nucleons, R. E. Peierls, presiding.

SEGRE opened the session by giving a discussion of the experiments performed at the Bevatron leading to the discovery of the anti-proton and to some of its properties.

Theory had predicted the existence of anti-protons long ago and there had been serious attempts to find them in the cosmic radiation. Only three events which could have been anti-protons had been reported by cosmic ray workers and all of these events suffered from lack of some information that would have pinned down the determination of the identity of the particle concerned. These events were reported by Cowan* (Phys. Rev., 94, 161 (1954)), Bridge, et al. (Phys. Rev., 95, 1101 (1954)) and Amaldi et al. (N. Cim. 1, 492 (1955)).

The experimental discovery of the anti-proton at the Bevatron involved the determination of its negative charge and protonic mass. The same series of experiments included a determination of the frequency of antiprotons produced in Cu compared to π^- - mesons as a function of the circulating proton beam energy (i.e. an investigation of the threshold production energy). The fact that the antiprotons fly 80 feet with a velocity .78c in the experiment is at least a limited indication of their stability. These experiments have already been published and the reader is referred to Chamberlain et al. (Phys. Rev., 100, 947 (1955)) for the results mentioned above and the experimental arrangement. It

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*Editor's note: The Cowan event is more probably to be interpreted as a V^0 event having a negative electron secondary and a positive π-meson secondary.

should, however, be pointed out that one of the great difficulties of this experiment lay in the fact that each anti-proton was accompanied by about 50,000 π^- mesons and consequently very powerful discrimination was needed to detect the anti-proton in this large background.

In order to study the annihilation process of anti-protons by a simple and quick method, they were sent into a Ĉerenkov counter of Pb glass (Brabant, et al., Phys. Rev., 101, 498 (1956) and Brabant et al., UCRL-3302) where one could see the Ĉerenkov pulses produced by showers resulting from the annihilation process. The counter was calibrated with pions. The pulse height distribution for π-mesons and for anti-protons is shown in Fig. 1. The anti-proton distribution, shown by the histogram, is clearly different from the π-meson distribution as shown by the smooth curve. A later curve given by Brabant et al., UCRL-3302, shows anti-proton pulses extending out to 1.1 Bev with an uncertainty of about 30 per cent owing to calibration problems. It is well to point out that these Ĉerenkov pulses represent lower limits to the energy released since neutral particles and slow

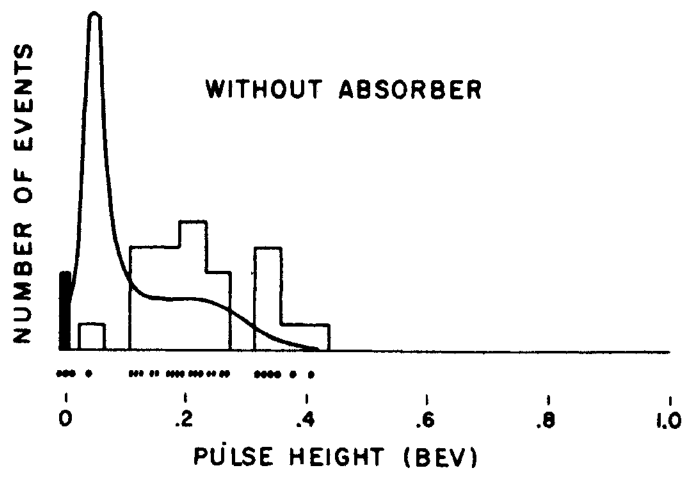


Fig. 1

particles escape detection.

There were several indications that anti-protons had an anomalous cross section, i.e., were easily absorbed by matter. "The first symptom was that Teller said it." The second was that anti-protons did not seem to reach the second half of the lead glass Cerenkov counter. It was decided to measure the anti-proton attenuation cross-section. The apparatus is shown in Fig. 2. This detector was placed in the 1.19 Bev/c anti-proton beam. The anti-protons enter the plastic scintillator S_3 with an energy 497±10 Mev. and a velocity of $\beta = 0.75$. They then enter the absorber (beryllium and copper were used). The Čerenkov water counter C3 has a threshold at $\beta = 0.75$ hence does not detect anti-protons which pass through without annihilating. S_4 is a plastic scintillator. Now if an anti-proton passes undisturbed through the apparatus it would give a signal in S3 and S4 but not in C3. If it is scattered elastically it would give a signal in S3 and no signal in C3 or S4.

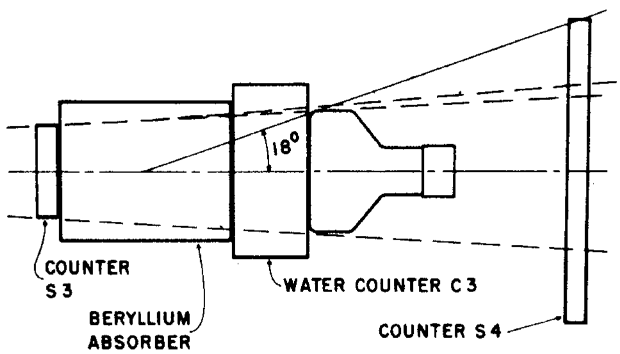


Fig. 2

If it is annihilated with emission of fast charged particles it will actuate S3, C3, and, perhaps, S_4, depending on the direction of flight of these charged particles. It is, however, possible that if it annihilates,

Material:	Cu	Be
Kinetic energy Cutoff angle	500-350 Mev 13^{o}	500-400 Mev 19^{o}
Attenuation cross section for p^{+}	0.78 ± 0.07b.	0.178 ± 0.013b.
Attenuation cross section for p^{-}	1.58 ± 0.22b.	0.365 ± 0.059b.
Geometrical cross section ($r_0 = 1.3\ A^{1/3}$)	0.84b.	0.23b.
Ratio $\sigma_{p^-}/\sigma_{p^+}$	2.02 ± 0.33	2.05 ± 0.36
Fraction annihilation (lower limit)	65%	51%

Fig. 3

ANTIPROTON INTERACTION CROSS SECTION
IN NUCLEAR EMULSIONS

(Preliminary March 28, 1956)

ΔR_p-cm	ΔT_p-Mev	L cm	$N_{annihil}$	N_{scat} (>20°)	λ cm	r_o
0.2-3.6	20-110	61.5	6	1	8.8	2.5
3.6-10	110-200	145.5	6	1	20.7	1.6
0.2-10	20-200	196	12	2	14±4.5	1.9±0.3

$$\sigma = \pi(r_o\ 10^{-13}\ A^{1/3})^2$$

Fig. 4

it could send the annihilation products in directions so as to miss C3 and S4. This seems fairly unlikely. Still, the fraction of the cross-section due to annihilation obtained in this experiment is a lower limit because of this possibility. Counter S_4 subtended an angle of 18° with the target for beryllium and 12° for copper. These angles were chosen so that diffraction scattering would not count.

Figure 3 shows the results for copper and beryllium. The attenuation cross-section is measured by the same apparatus for positive protons as well. In the fifth row we see that the ratio of $\sigma_{p^-}/\sigma_{p^+}$ is very closely 2 for both copper and beryllium. The last row shows the fraction due to annihilation and should be understood as a lower limit. (See Chamberlain, et al. UCRL-3327 for a complete description of this experiment.)

Figure 4 contains some preliminary data from nuclear emulsions on the anti-proton interaction cross-section. Note that there are only 12 annihilation events and 2 scattering events in all and consequently the statistics are certainly bad. However, these preliminary emulsion results again indicate a cross-section substantially larger than geometric.

The first emulsion irradiation was done using the first half (one deflecting magnet and one magnetic lens) of the system used in the anti-proton experiment of Chamberlain et al. Since the range of the anti-protons from the selected beam was considerably greater than the length of the stacks, a copper absorber of 132 g/cm^2 was inserted before the emulsion in order to slow them down so that they would come to rest in the emulsion. This irradiation was done before the large absorption cross-section was known. After a very large amount of work scanning, only one anti-proton star was found. (See Chamberlain et al. and Amaldi et al., Phys. Rev. 101, 909 (1956), N. Cim. 3, 447, (1956) and UCRL-3224).

In view of the fact that the cross-section in copper is about twice geometric, the low yield is explained. A new irradiation was planned in which (1) no absorbing material preceded the stack, (2) the range of the anti-protons ended in the stack, and (3) anti-protons and mesons were easily distinguishable by grain density at the entrance of the stack. In order to achieve these results, it was necessary to select anti-protons of lower momentum, at the expense of a larger π^- meson background (5×10^5) than at higher momenta. In this experiment 700 Mev/c

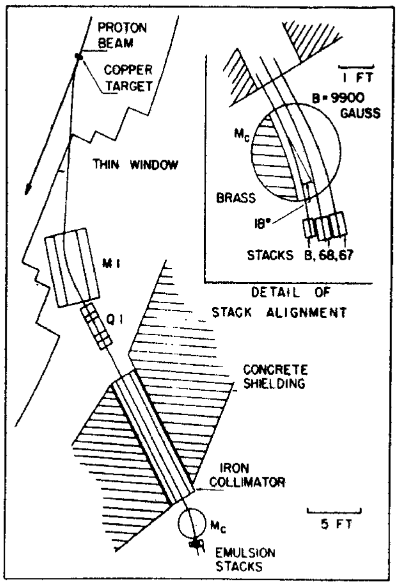


Fig. 5

Fig. 6

momentum was used instead of 1090 Mev/c. The irradiation geometry is shown in Fig. 5. The plates so irradiated were divided up among several groups at Berkeley and the Rome group. The total number of stars obtained so far is 27. Not all of the events have been analysed yet. Clearly the first thing of interest was to find a star in which the visible energy was larger than 938 Mev. This would be the most direct proof that one actually had direct annihilation. Fig. 6 shows the Rome star produced in the first irradiation and Fig. 7 shows the visible energy of the star prongs. The total visible energy is 826 Mev. The minimum additional energy resulting from the un-balance of momentum (520 Mev/c) is 65 Mev, hence the guaranteed energy released is 891 Mev. This is near 938 Mev but not absolute proof of the annihilation process.

Figure 8 shows another star produced during the second irradiation. In this event, an anti-proton comes to

Antiproton star RB1

Track	Identity	Kinetic energy Mev	Visible energy Mev
a	π	332	472
b	π	57.5	197
c*	p	32.3	40
d	p(?)	15.0	23
e	p(?)	7.6	16
f	p(?)	5.5	13
g	p(?)	31.4	39
h	p(?)	5.5	14
i	p(?)	3.6	12
Total visible:			826
Minimum from unbalance (520 Mev/c)			65
Guaranteed energy release			891

Fig. 7

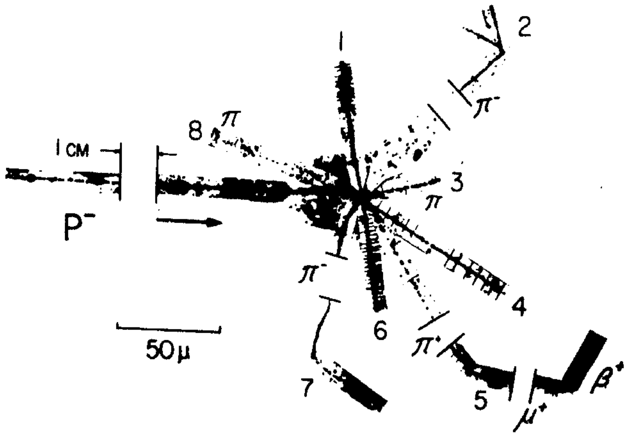


Fig. 8

rest and produces the star. (Observed by A. G. Ekspong.) Figure 9 shows a table of the measurements relating to this event. It is evident from this table that the visible energy released is considerably above 938 Mev. This star therefore shows clearly that the annihilation process is taking place.

Table II

Measurements and data on the eight prongs of the P^- star shown in Fig. 1

Track number	Range mm	Number of plates traversed	Dip angle	Projected angle	pβ Mev/c	Ionization g/g_o	Identity	E_{kin} Mev	Total energy Mev
1	0.59	2	-56.5°	103°			p (?)	10	18
2	27.9	11	$+6.5^\circ$	61.5°			π^-	43	183
3	>50	81	-73.5°	14.5°	250±45	1.10±0.04	π (?)	174±40	314±40
4	>14.2	16	$+53^\circ$	318.5°			p (?)	70± 5	78± 5
5	6.2	3	$+4^\circ$	305.5°			π^+	30± 6	170± 6
6	9.5	15	-63.5°	281°			T(?)	82	98
7	18.6	30	-83.5°	255°			π^-	34	174
8	>22.3	16	$+33^\circ$	163°	190±30	~1	π (?)	125±25	265±25
							Total visible energy:		1300±50 Mev
							For momentum balance:		≥100 Mev
							Total energy release:		≥1400±50 Mev

Fig. 9

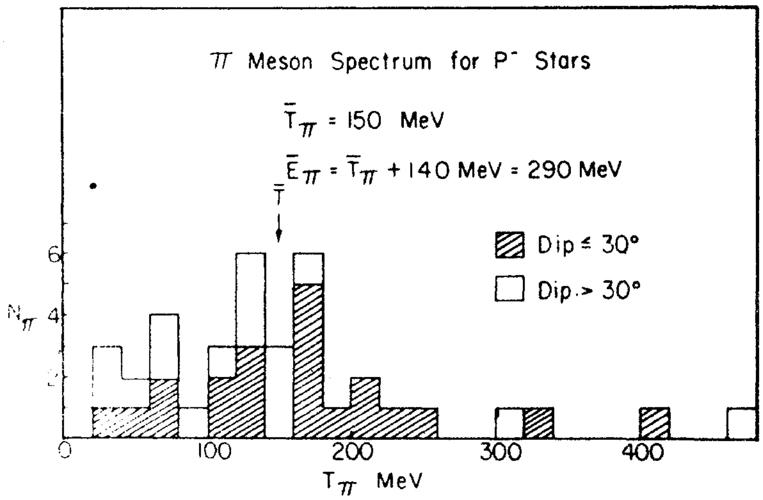


Fig. 10

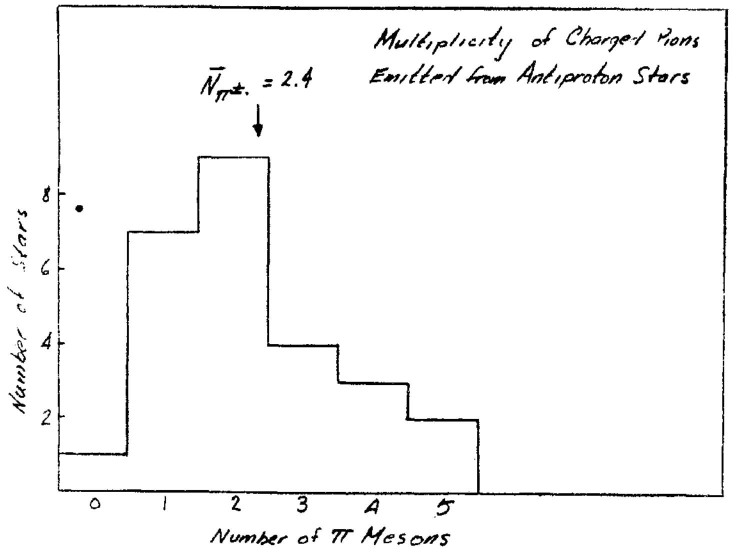


Fig. 11

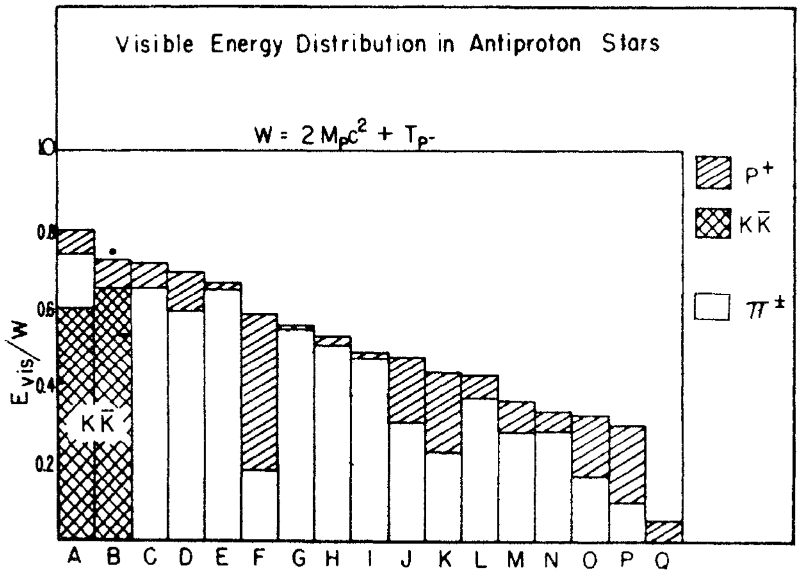


Fig. 12

Figure 10 shows the π-meson spectrum for p⁻ stars. The average kinetic energy is 150±80 Mev. Figure 11 shows the multiplicity of π-mesons emitted from p⁻ - stars. The average multiplicity is $N_{\pi^\pm} = 2.4$. The charge of the π-s is usually unknown since they generally leave the emulsion stack. Only 6 π's have had their charge determined, one π^+ and 5 π^-. This is only 6 out of about 50 π's observed. Figure 12 shows the visible energy distribution in the p⁻ - stars analysed, broken down into the contributions from various particles. Notice that energy has been normalized to the quantity $W = 2M_pc^2 + T_{p-}$, the total available energy where T_p - is the kinetic energy of the p⁻. Note also that there are 2 cases in which K-particles were produced. One of these K's may be wrong, (i.e. it really may not be a K). Both of these particles end outside of the emulsion. The energy associated with them takes into account the fact that they are presumably produced in association with a second particle (to conserve strangeness).

Figure 13 shows the average value of the energy for the various particles occurring in p^- - stars. Again the normalization is to $W = 2M_pc^2 + T_{p-}$. It must be noted that the error on the average charged π-meson energy per star is of the order of $^{+300}_{-200}$ Mev. and the error on the average energy of the protons is ± 80 Mev. Observe that the amount of energy available for π's depends critically on the number of K's observed. Since the number of K mesons (1 or 2) is not well known, the energy available for π^0 's is consequently not well determined.

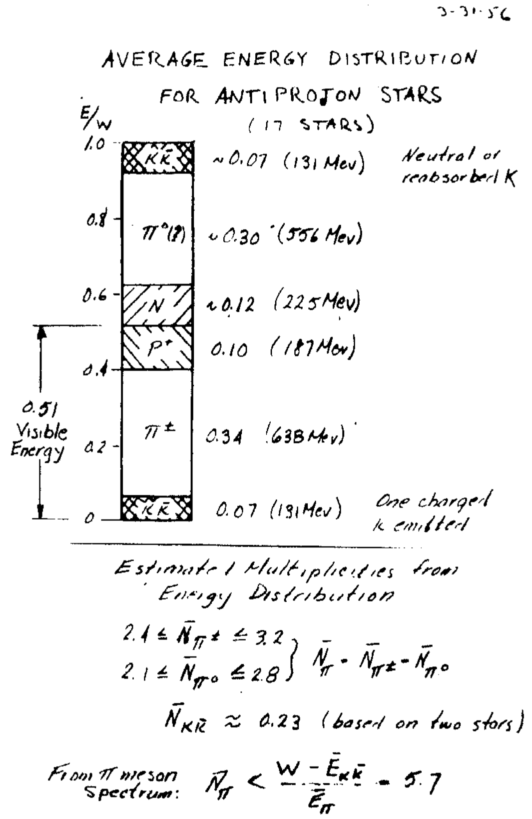


Fig. 13

Of the two cases of scattering of p^-, (see Fig. 4) one case seems to be appreciably inelastic, the energy loss being of the order of 30 Mev. Another point of interest is charge exchange. This is interesting because it will be the method of finding anti-neutrons. One sends antiprotons through matter, and then observes large stars produced by neutral particles. So far there is only one doubtful case seen in a stack at higher energy. Thus charge exchange does not seem to occur a large fraction of the time, but could occur with a frequency of 5 - 10 per cent.

Discussion

Rossi asked what the maximum energy carried away by visible π-mesons in the p^- - stars was. It is 638 Mev. (See Fig. 12). Teller asked if anyone could reconcile the small number of anti-protons observed in cosmic-rays using the large interaction cross-section for anti-protons. Amaldi replied that he would say something about this later. In response to a question by Leprince-Ringuet concerning the average number of π-mesons emitted in ordinary stars having the same center-of-mass energy as that available in p^--p annihilation, Friedlander replied that from stars produced by 4.5 Bev π mesons the average number of shower particles is 2. However, one must recall that in p^- stars the original laboratory momentum is essentially zero. Kaplon commented that the conditions were so different as to make a meaningful comparison practically impossible.

ROSSI made a few remarks about the further analysis of the "prehistoric" M.I.T. antiproton event.

"In 1954, the M.I.T. group described a cosmic-ray event which could be naturally interpreted as the annihilation of an antiproton. The energy set free in this process appeared in the form of γ-rays, presumably arising from the decay of π^0-mesons. Through an analysis of showers produced by electrons of known energy in a multiplate chamber similar to that used by the M.I.T. group, Hazen was able to set a lower limit of 1630 ± 320 Mev to the energy of the secondary γ-rays.

"Recently David Caldwell and Yash Pal at M.I.T. have perfected a photometric method for the measurement of ionization in multiplate cloud chambers. This method allows one to determine the mass of particles stopping in such chambers. We used the photometric method to re-analyze the M.I.T. antiproton event, and found a value of 823 ± 155 Mev for the rest energy of this primary particle. As a check, we made similar measurements on the tracks of K-mesons and found a value of 488 ± 80 for the rest energy of these particles. There is thus little doubt that the M.I.T. event was indeed the annihilation of an antiproton. The interest of this result lies in the fact that, of all annihilation events reported so far, the M.I.T. event has perhaps the largest visible energy release and is the only one providing direct evidence for the production of π^0-mesons."

AMALDI discussed p^- events found in cosmic-rays, with particular reference to their frequency of occurrence. Two events have been observed in emulsions exposed to cosmic rays at high altitude, which can be interpreted as due to antiprotons. The first has been already mentioned by Segre, the second has been observed by the Bern group (Teucher, Winzeler and Lohrmann). Each of them was found by scanning for double stars about 10^2 cm^3 of emulsion exposed for 8 hours at about 27 Km and containing 17 events per cc of energy larger than 5 Bev.

In both cases one observes the star in which the antiproton is produced as well as the annihilation star. Their more peculiar feature consists in the very low energy (4 Mev and 7 Mev) of the antiprotons in the laboratory system, while the energy of the mother star is rather high ($\geqslant$ 7 Bev and $\geqslant$ 12 Bev).

The fact that only low energy antiprotons (let us say with $T \leqslant 10$ Mev) are observed, is due to the experimental bias introduced by the scanning technique, which strongly favours the observation of double stars when the connecting track is so short as to make them appear in the same field of the microscope.

One can now try to see whether these observations do fit, within extremely wide limits, the observed rate of production of antiprotons at the bevatron. Such a comparison involves obviously various uncertain factors, but one can show that by taking all these factors in the sense to give a large rate of production of antiprotons, the value of the volume of the emulsion exposed to cosmic rays in which one low energy antiproton is expected to be found, turns out to be much too high. For instance, taking the yield of antiprotons per star equal to 10^{-4} i.e. of the order of 100 times that observed at the bevatron, one gets not less than 10^5 cm^3.

Now it is true that a few other laboratories different from those of Bern and Rome have also scanned comparable amounts of emulsions in a similar way, without finding any antiproton, but it is clear that this circumstance may explain a factor 10, but certainly not a factor 10^3 between this estimated volume and that actually scanned.

Therefore one can conclude that the two low energy antiprotons observed until now in nuclear emulsion exposed to cosmic rays are certainly too many with respect to what one would have expected. Obviously this may be due to a large fluctuation. One can not, however, disregard the possibility that this observation may be due to some physical reason.

An increase still larger than that adopted ($\sim 10^2$) of the yield from the bevatron to cosmic rays energies would help. But it may be worthwhile to mention that a reduction of the discrepancy would be obtained if the low energy antiprotons would represent a fraction of the total number of produced antiprotons, larger than that adopted in the above estimate: $\leq 10^{-2}$, a value certainly not ungenerous if calculated taking into account the motion of the center of mass in a nucleon-nucleon or pion-nucleon collision in a nucleus. For instance a few elastic (or inelastic) collisions against the nucleons of a heavy nucleus in which the antiproton is produced, could contribute quite appreciably to enrich the low energy tail of their spectrum.

Discussion

Bernardini suggested that an analysis of the Amaldi type would yield quite different results for cloud chambers because the biases are so different. He asked Rossi if he had made a similar analysis for cloud chambers. Rossi answered in the negative. Hyams indicated that he had made such an analysis and that it was extremely improbable that a p^- should have been seen in cloud chambers.

Bernardini asked what method was used to estimate the energy going into π^0-s. Segre said, they assumed that the average energy of neutral and charged mesons was the same. Bernardini asked why no events of the Rossi type had been found among the Berkeley p^- stars. Segre answered that one which had been found was nearly like the Rossi event. But for an event of this type in which the p^- does not form a star at the very end of its range, it is hard to be certain that one does in fact have an antiproton.

Leprince-Ringuet suggested that if Berkeley's ratio of 50,000 π-s per p^- held in cosmic ray stars as well, then Amaldi should have seen 50 π's per star.

S. Goldhaber commented that, by two different methods of calculation, one arrives at between 5 and 6 as the π meson multiplicity in p^- stars.

a) If you look at all pions in the 30^o cone in which the energy can be determined well, you get an average energy of 150 Mev. The total energy available for pions divided by 150 Mev gives the above multiplicity.

b) The other approach is to look at the upper limit on the number of charged pions, including those identified, plus an estimate of those occurring among the "evaporation" prong. This gives 3.2 as an upper limit for charged π's. Invoking charge independence gives 1.6 π^o-s or a total of 4.8 π-s. Both estimates fall in the region of multiplicity 5 - 6.

Segre observed to Amaldi, that the p^-/π ratio was worse by a factor 10 or so at lower momentum in the Berkeley observations. Amaldi answered that he thought this could be due to more copious π production at lower energy, and need not contradict his conjectures.

MARSHAK discussed two calculations concerning the annihilation of anti-nucleons. He first reported some figures handed to him by Silin and calculated by Belenky and collaborators using the Fermi statistical model. These figures are given in Table I. (a), (b) refer to total π production in $p\bar{p}$, $n\bar{n}$ and $p\bar{n}$, $n\bar{p}$ annihilation. The π-mesons are taken to be relativistic.

Table I. Belenky, Nikishov, Rosental, Maximenko.

Distribution of number of prongs in stars formed by annihilation of antinucleons at rest.

a) $p\bar{p}$ and $n\bar{n}$ annihilations

Total number of mesons	2	3	4	5
Frequency relative to 2-meson annihilation	1	7.6	7.3	2.7

b) $p\bar{n}$ and $n\bar{p}$

Total number	2	3	4	5
Frequency relative to 2-meson annihilation	1	5.1	5.4	1.9

Distribution of number of charged mesons

c) $p\bar{p}$ and $n\bar{n}$ annihilation

Number of charged mesons	2	3	4	5
Frequency relative to 2-meson	1	0	0.37	0

d) $p\bar{n}$ and $n\bar{p}$ annihilation

Number of charged mesons	1	2	3	4	5
Frequency relative to 1-meson annihilation	1	0	2.5	0	0.2

Marshak noted the average multiplicity was about 3.7 for the two groups (a) and (b) taken together. The radius of the interaction volume was $\hbar/\mu c$, where μ is the mass of the π-meson. (c) and (d) refer to charged meson production only, in $p\bar{p}$, $n\bar{n}$ and $p\bar{n}$, $n\bar{p}$ annihilation. Marshak then reported on π multiplicity values calculated by G. Sudarshan working with Marshak at the University of Rochester. (See "Note on the Annihilation of Anti-Nucleons" by George Sudarshan - submitted to the Physical Review.) The expected π and K-meson multiplicities resulting from the annihilation of a nucleon - anti-nucleon pair at rest were calculated using the Fermi statistical model and the Pomeranchuk-Landau statistical model which includes final state interactions of the mesons. The Fermi model yields smaller pion multiplicities and larger probabilities for K meson pairs than does the Pomeranchuk-Landau model. Table II shows the result of these calculations for the case where the π's are taken as relativistic and the K's non-relativistic. Rigorous conservation of linear momentum and isotopic spin has been used but not conservation of angular momentum. Marshak noted that the average pion multiplicity as calculated with the Fermi model differed by about one between Belenky's calculation and the Rochester calculations. He did not have enough information on Belenky's work to be able to understand this discrepancy.

Table II

		$p\bar{p}$	$n\bar{p}$	Interaction radius	Model
Average pion Multiplicity	$\langle n_{\pi} \rangle$	2.3	2.4	$\hbar/\mu c$	Fermi
Per cent K production	p_k	23%	21%		Fermi
	$\langle n_{\pi} \rangle$	3.6	3.6	$\hbar/\mu c$	Pomeranchuk-Landau
	p_k	3%	2%	(Only π's Interact)	
	$\langle n_{\pi} \rangle$	3	3	$0.75 \frac{\hbar}{\mu c}$	Pomeranchuk-Landau
	p_k	9%	8%	(Only π's Interact)	
	$\langle n_{\pi} \rangle$	2.8	2.8	$0.75 \frac{\hbar}{\mu c}$	Pomeranchuk-Landau
	p_k	18%	16%	(Both π's and K's Interact)	

The statistical model makes some sense as a method of calculating this annihilation process for two reasons (1) The large interaction cross-section observed is consistent with the Fermi-interaction radius $\hbar/\mu c$ (2) In the c.m. there is 2 Bev available energy which is a large amount indeed.

Discussion

Peierls commented that it was indeed a good idea to make these calculations of expected multiplicities. He cautioned, however, that next to nothing is known about annihilation in hydrogen. Observations so far have been made only in complex nuclei and what one sees coming out of nuclei is certainly different from what one would see from a bare nucleon - anti-nucleon annihilation.

Note added by Silin in proof. The difference between Belenky's calculation and Marshak's calculations is mainly due to the fact that in Marshak's calculation the statistical theory was applied to the production of K-mesons, but in Belenky's calculation it was not. Belenky and his collaborators believed that the statistical theory is not applicable to the production of K-mesons, as it gives too large a value for their number. For instance, in the collision of π-mesons with nucleons at the energies of 1.37 Bev and 4.5 Bev, the number of K-mesons calculated with the statistical theory is 10 times the experimental value, while the number of π-mesons is in good agreement with experiment.

TELLER discussed his proposed explanation of the strong anti-nucleon - nucleus interaction. A close paraphrase of his talk follows. To understand the background of these ideas it is necessary to go back to a model of the nucleus first proposed by Johnson and Teller (Phys. Rev., 98, 783 (1955)) and extended by Duerr and Teller (Phys. Rev., 101, 494 (1956)).

You can, as a starting point, take the independent particle model of the nucleus completely literally, i.e., assume that nucleons have definite orbits in nuclei and thus possess separable wave functions. If you assume that binding in a nucleus depends on pions which carry either charge or angular momentum or even the pseudoscalar property then in every emission or absorption of such a meson, you change the state of the nucleon. Thus it would be nice, at least in the non-relativistic case, if these mesons and hence fields were neutral and scalar. Such mesons would give rise to the kind of potential you would expect on the simplest grounds. These mesons would not be "strange" particles since they must interact strongly with nucleons. Since they are also neutral and scalar they would promptly disintegrate and would not easily be observable. In fact they might be virtual states of two interacting pions and as such might be connected with the pion-pion interaction which has been discussed at this conference. Johnson and Teller began with the interaction

$$-A\psi^{*}\psi\phi + B\nabla\psi^{*}\nabla\psi\phi$$

which is linear in this new meson field ϕ. The repulsive term does not appear as a function of position but is proportional to the kinetic energy of the nucleon. The constants A and B can be determined to give the correct binding energy and density to nuclear matter. The second term has the same dependence on momentum as the kinetic energy term. Hence they can be taken together as a single term of the form

$$\frac{1}{M_{eff}}\ p^2 .$$

When the constants are adjusted as suggested above, $M_{eff} \cong 1/2\ M_{nucleon}$ and all kinetic energies in nuclei are about twice as large as you would expect. This is a very considerable difference. Using an entirely different approach, Brueckner too has arrived at an effective mass of this order of magnitude. Phenomenologically, such an effective mass is not an unreasonable idea in describing nuclear properties. Brueckner's approach and the Johnson-Teller approach do not differ much as long as one restricts oneself to phenomena in which the nucleon kinetic energy stays somewhere in the vicinity of the Fermi sea, and one may consider it a phenomenological description of nuclei.

Now in connection with experiments in which mesons are involved, it might be well to remember that for nuclear forces themselves it may be more reasonable to work with a reduced mass at least as long as the energy received by the nucleons does not exceed 10-20 Mev. This may change some estimates currently being made. Some attempts have been made at Berkeley at interpreting low energy nuclear phenomena using this approach.

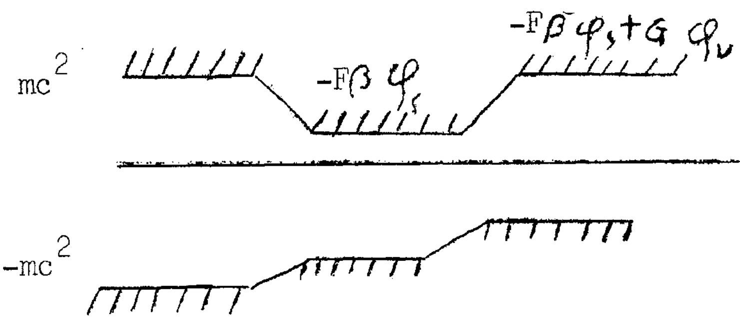
Two other classes of phenomena seem adequately explained. These are: (1) the approximately correct ratio of proton and neutron numbers and energy levels in stable nuclei and (2) nuclear frequencies. In such a theory all kinetic energies are doubled, the momentum distribution must stay the same because it is determined by the uncertainty principle, the velocities are doubled and the frequencies are doubled. There are rather marked effects which appear to correspond to reality. One might point out that this theory tries to account only for the volume effects in the nucleus and should not therefore be asked to yield fine details which might arise primarily from surface phenomena.

The generalization of the theory to the relativistic case has been carried out by Duerr. He found that, as in the non-relativistic case, one needs two interactions or two fields. Now a scalar in the non-relativistic approximation can be generalized to the relativistic case in one of two ways. Either (i) as a relativistic scalar or as (ii) the fourth component of a normal relativistic vector. Duerr has used both of these in the following Dirac equation for a nucleon, picked arbitrarily from the several possibilities available:

$$E = c\alpha \cdot p\,\psi + mc^2\beta\psi - F\beta\varphi_s\psi + G\varphi_\nu\psi$$

Note that the interaction constants are not the same as in the non-relativistic approximation. φ_s is a relativistic scalar and φ_ν is the fourth component of a relativistic vector. The other three components of the vector should also be included, Teller commented, but they arise from surface terms and contribute little or nothing to volume effects. They must, of course, be included when making a detailed theory. The constants F, G are adjusted so as to give A, B in the non-relativistic limit. Note that the term with G does not depend on energy but that the one with F decreases with increasing energy since $\beta \cong mc^2/E$. One can now adjust the difference of these two terms so as to give nuclear attraction of about 100 Mev. Then the F must be $\sim$500 Mev and G $\sim$400 Mev. This will then give the empirical dependence for the non-relativistic limit. Teller brought up the fact that this subtracting of two large numbers to get a small one may seem like an unattractive idea. He suggested that it might be tested in high energy scattering experiments, since the attractive term should go to zero and only the repulsive term would remain. High energy protons or neutrons should be scattered on nuclei and not on nucleons. Another point is that from the above equation one can calculate the spin-orbit coupling. The spin-orbit coupling produced by a scalar and a vector give opposite signs apart from the coefficients. So if the coefficients are of opposite signs to begin with, then the spin-orbit coupling constants add. This gives a sufficiently large Thomas coupling to account for the empirical spin-orbit coupling, actually, to account for it embarrassingly well, since spin-orbit coupling is essentially a surface phenomenon.

Now for the antiproton, the scalar attraction remains the same as for a nucleon, but the fourth component of the vector repulsion becomes an attraction, i.e. an attraction between opposite nuclear charges. This can be represented in an energy level diagram (see Phys. Rev. 101, 494 (1956)).



The question is how to observe this. Most people looking at this diagram think that one can make nucleon - anti-nucleon pairs with only 1 Bev. This is cheating, since even if you make them the p^- is held so strongly in the nucleus that it cannot escape. One has to put in 2 Bev to let it escape as well. The actual threshold may be slightly smaller in this theory but not greatly. One simple conclusion comes from this kind of theory; namely an antiproton will be drawn into ordinary nuclear matter near the surface of the nucleus with very strong forces. You can estimate the attenuation cross-section. Duerr found that for copper it is

2.15 times geometrical, including scattering angles up to 13^{o}. This has a large uncertainty in it however. For Be, Duerr estimated 2.50 times geometric.

Teller then pointed out that the big cross-section itself could be compatible either with attraction or repulsion. However, attraction implies that the particle is drawn into the nucleus. Hence the annihilation process would be an important part of the cross-section. This seems to be the case experimentally. Furthermore if an antiproton undergoes strong scattering without being pulled into the nucleus, then it should receive some transverse momentum and at the same time excite the nucleus. Teller pointed out that there exists one event which answers to this description, - a p^- inelastic scattering with an energy loss of about 30 Mev.

Teller's last comment concerned the Fermi-Yang suggestion of a few years ago that π-mesons were only tightly bound pairs of nucleons and anti-nucleons. He said that perhaps most people did not take that idea very seriously since that meant inventing "a glue to glue the glue." However now, in this new theory, since one needs a neutral and invisible "glue" anyway for different reasons one might see if π-mesons could be explained as "generalized positronium."

Discussion

Marshak suggested that the pion itself could act as a husky glue between the nucleon and the anti-nucleon. There is an extra virtual annihilation diagram which one doesn't get between two nucleons. He suggested this should be investigated further, specifically to see if it could account for the large cross-section without requiring new "glue." Touschek commented that this Marshak type of interaction would be of very short range and one needs a long range interaction to explain the experiment. Peierls said he did not know if such an interaction was necessarily of short range. Feynman pointed out that the energies obtained from this theory would not be positive-definite. The potentials are large enough to represent an appreciable fraction of mc^2. The attraction of a nucleon-antinucleon pair turns out to be so strong that their energy is much less than the rest mass of the two parts. Suppose one now considers a system composed of a number of pairs. The effect of the vector part of the interaction is that the nucleons repel each other and attract the antinucleons. The vector contributions more or less cancel out therefore. The scalar potential adds, however, so that the total energy would become negative if a sufficient number of particles are used. So, if one assumes this theory, "the Hamiltonian has no lowest energy, and this universe will fall through a hole somehow." Teller: "On Feynman's suggestion, we have tried to peer down these holes, but not with any feeling that one necessarily has to fall into them when they appear to be there." Whether these holes are dangerous or not, depends on whether a certain generalized $e^2/\hbar c$ is greater or less than unity. If the interaction is strong enough, the holes are there and are dangerous. One possible way to escape the difficulties is to assume that only the vector part of the interaction is basic, and that the scalar part is due to a pair of vectors. This would give an attraction. Perhaps one can make the theory convergent, if what we see so far is not the basic interaction, but the summation of interactions in all approximations. But in the first approximation, Teller wouldn't shy away from a theory which even had some chance of diverging.

Williams asked how one prevents the pions from contributing to nuclear forces. Teller answered that he was certain that on the surface of the nucleon the pions must contribute a lot. In the interior, i.e. in the momentum sphere, when you try to emit a pion you throw a nucleon into a new orbit. If that orbit is occupied then the virtual emission of the pion does not contribute. Therefore the pion can contribute in the interior only if the forces are very strongly fluctuating. Such fluctuations can give rise to situations like the shell-model as has been shown by Brueckner. Teller added that he did not wish to imply that pions could not give rise to nuclear forces, but he did think that the opposite point of view was, though simple minded, not complete nonsense. Sachs pointed out that if the fields acting to glue nucleons and anti-nucleons together to form a π-meson are neutral, there should be two π^0 mesons, one in the triplet, the other in the singlet isotopic spin state. Presumably the two π-s would have the same mass. Teller answered that his comment on generalized positronium was thrown out only as a suggestion and he wasn't prepared to defend such advance outposts of the theory.

Feynman said that the long ranges required to account for the cross-section imply a fairly small mass for the particles referred to in Teller's theory. What mass would they have and should we have found them already? Teller answered that their mass should be about twice the pion mass. This is a very rough estimate. Bernardini said they should contribute to Compton scattering at high-energy. Teller answered that they are all neutral. Dyson asked if predictions had been made about the elementary cross-sections (i.e. antiproton-proton cross-section). Teller said none had yet been made. Sachs asked if it was really the range of the reaction or was it the nuclear fuzz which was significant for the cross-sections. Teller thought that perhaps a good part of the cross-section size was due to the nuclear fuzz. Yang asked why when an annihilation process takes place shouldn't many of these "new mesons" be formed. Teller replied that perhaps they were but could decay into, say, two π mesons within few nuclear diameters. Frisch asked whether the excitation of the nucleon to the S = 3/2, T = 3/2 state by a gamma ray should have the same resonance character, as a function of energy, for nucleons in nuclei, as for free nucleons. Teller said he had no answer. Schiff noted that if π mesons came from these "new mesons" which had gone several nuclear diameters after the annihilation process then there should be an angular correlation which could be observed. Teller said yes, but the kinetic energy of the particle would tend to fuzz this up a bit. Breit suggested this theory might work as well if the scalar term was omitted. Teller concurred but suggested it was then an entirely different approach. Primakoff suggested that the nuclear magnetic moment would be considerably affected by this theory. Teller concurred.