Antiproton Annihilations in Propane*

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An experiment to study the $\bar{p}$ annihilation process at 1.05 Bev/c was performed with the Lawrence Radiation Laboratory 30-in. propane bubble chamber. It was observed that the K-meson production in annihilation events rises sharply with the increase in energy, namely from $4\pm1\%$ for annihilations at or near "rest" to $8\pm1\%$. On the other hand, the pion multiplicity was not observed to increase appreciably with the increase of available energy. We have found a pion multiplicity of 5.0 ± 0.2. These numbers are discussed in this paper and compared with existing models for the $\bar{p}$ annihilation process. It is pointed out that with further increase in bombarding energy different models may differ appreciably in the above quantities.

We have observed a $\bar{p}$-H annihilation cross section of 51 ± 10 mb and a $\bar{p}$-C annihilation cross section of 368 ± 60 mb at a $\bar{p}$ momentum of 1.05 Bev/c. Crude determinations of the $\bar{p}$ charge-exchange process—which turns out to be forward peaked— and of $\bar{p}$ inelastic-scattering events leading to pion production are also discussed.

I. INTRODUCTION

SINCE the antinucleon-nucleon annihilation was first discovered, a number of studies of the annihilation process have been carried out. Those studies dealt mainly with the analysis of annihilation stars at rest and some with energies up to $T_{\bar{p}}=150$ Mev.[1–5] Some of the salient features of the analysis of the annihilation products are: (a) Pion production is the most prevalent product of the annihilation. (b) The pion multiplicity is of the order of five. (c) In about 4% of the annihilation events pairs of K mesons are produced.

Attempts to understand this many-body process led to a number of serious difficulties. The first attempt to interpret the annihilation process was a comparison of the experimental results with those predicted by the statistical model. It was found that the predicted pion multiplicity as well as K-meson production were in disagreement with the experimental results. When the radius of interaction was taken as a free parameter, it was possible to fit the annihilations leading to pure pion production, if this parameter was increased to a magnitude of about 2.3 pion Compton wavelengths. Once this parameter was suitably adjusted to fit the mean pion multiplicity, experimental results such as the multiplicity distribution, the pion momentum spectra, and the distribution of angles between pairs of pions were in agreement with the model when pion charges are disregarded. However, the K-meson production fell far below its predicted value. The large interaction volume needed to fit the experimental pion data still remained unexplained and is devoid of direct physical meaning. A number of modifications of the statistical model were proposed introducing dynamic processes such as strong pion-pion interactions in the form of pion-pion isobars.[6,7] Koba and Takeda proposed a two-step annihilation process in which core annihilation with pion production precedes the release of pions from the pion clouds of the nucleon-antinucleon system.[8] All these models were adjusted, however, in one way or another to the observed average pion multiplicity. One must thus look at finer details in order to distinguish between the models or arrive at a new clue.

The present experiment was designed to investigate the annihilation process in greater detail at a momentum of 1.05 Bev/c corresponding to a total energy in the center-of-mass system of $W=2.1$ Bev. Our emphasis in the analysis of the data was the study of K-meson production, angular correlation in pion production,[9,10] and variation of pion and K-meson multiplicities as a function of the total available energy. In addition, we were able to obtain an independent measurement of the annihilation cross section in carbon and hydrogen at a $\bar{p}$ momentum of 1.05 Bev/c. A crude determination of the charge-exchange interaction and an order-of-magnitude estimate of the inelastic $\bar{p}$ interactions leading to pion production were also made.

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The angular-correlation studies between pion pairs have shown a marked dependence on the charge of the pions. Namely, the like-pion pairs are observed to be emitted with smaller pair angles on the average than the unlike-pion pairs. This effect,[9] as well as a model which takes into account the influence of Bose-Einstein statistics in order to explain the effects, have already been discussed previously.[10] As has been pointed out in reference 10, if the approach considered there is correct, the radius of annihilation must be small.

In addition, it has also been pointed out by Pais[11] that the charge distribution of pions in annihilation events may be altered quite appreciably from the statistical model because of dynamic effects. In spite of these clear indications for the inadequacy of the large-volume statistical model, we will still use it in this paper for lack of a better model.

II. EXPERIMENTAL PROCEDURES

The present work was carried out using the Berkeley 30-in. propane bubble chamber with a magnetic field of about 14 kgauss. The 1.05-Bev/c $\bar{p}$ beam was highly purified by using two 20-ft electrostatic velocity spectrometers. The physical layout of the beam was that used for a preceding K^- experiment,[12] with the spectrometers retuned to transmit antiprotons. In two days of running time, 20 000 pictures were taken which yielded about 3000 annihilation events. The composition of the beam was determined by (a) a δ-ray study of the beam which was normalized to a similar study of a pion beam of nearly the same momentum, and (b) a study of the mean free path for the star formation in the "mesonic component" of the beam. This again was compared to a similar study of a pion beam of the same momentum. The $\bar{p}$ component of the beam was thus determined to be $38.5\pm7\%$ of the entire flux. The composition of the beam was found to be $\bar{p}:\mu^-:\pi^- = 1:1.3:0.3$. The uncertainty in the $\bar{p}$ component of the beam is the largest source of error in the cross-section measurements.

FIG. 1. Example of an $\bar{p}$ annihilation event yielding two charged K mesons. The reaction observed is $\bar{p}+``p" \rightarrow K^++K^-+\pi^++\pi^-+n\pi^0$. The K^+ meson decays in the τ mode, giving $\pi^++\pi^++\pi^-$. The π^+ mesons in turn show the characteristic $\pi^+\rightarrow\mu^+\rightarrow e^+$ decay. The K^- meson interacts in carbon (noncoplanar) giving a Σ^+ and π^-. The Σ^+ decays *via* the π^++n mode.

III. STRANGE-PARTICLE PRODUCTION

In the $\bar{p}-N$ annihilation there are four possible reactions leading to strange-particle production:

$$\bar{p}+N\rightarrow K^++K^-+n\pi,$$
$$\bar{p}+N\rightarrow K^0+\bar{K}^0+n\pi,$$
$$\bar{p}+N\rightarrow \bar{K}^0+K^++n\pi,$$
$$\bar{p}+N\rightarrow K^0+K^-+n\pi.$$

All four of these processes have been observed (see Table I and Figs. 1 and 2). In addition, we have observed Λ^0, Σ^+, and Σ^- hyperons associated with annihilation stars in carbon, which we interpret as most likely due to secondary interactions of K^- or $\bar{K}^0$ with a nucleon of the parent carbon nucleus. The charged K mesons can be identified with certainty only when decaying in the chamber. In the case of the neutral strange particles, our observations are restricted to the charged decay modes and for the K^0 meson, only to its short-lived $K_1{}^0$ component. These restrictions make the probability of observing a pair of strange particles very low. To arrive at the fraction of annihilation stars producing strange particles, we adopted the following method. We determined the detection efficiency for each strange particle separately and thus arrived at the total number of strange particles produced. Hyperons, which are included in this sample, are a manifestation of K^- or $\bar{K}^0$ production. Since strange particles must be produced in pairs in the $\bar{p}$ annihilation, the number of K-meson-producing stars is half of the total number of strange particles.

TABLE I. Number of annihilation events with a pair of identified strange particles. These events were observed in a sample of 3000 $\bar{p}$ annihilation events in propane at $P_{\bar{p}}=1.05$ Bev/c.

Particle	K^-	$\bar{K}^0$	Λ	Σ^+	Σ^-
K^+	5	2	6	0	0
K^0	1	6	2	1	3

A. Detection of K^0 Mesons and Λ Hyperons

For all V^0 events associated with annihilation stars, the Q value and the coplanarity of the line of flight and

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the decay plane were checked. As a further check, we also plotted the proper-time distributions for the K_1^0 mesons and Λ hyperons and found them to be in excellent agreement with the established mean lives.

From the measured momentum distributions of the K^0 mesons and Λ hyperons, it was estimated that 10% would escape detection by decaying outside the fiducial volume of the chamber. A nearly equal fraction of K_1^0 mesons and lambdas decay in the chamber; the fact that the mean life of the lambdas is longer is offset by their lower velocity at production. The total number of K^0 mesons was obtained by taking into account the nonobserved long-lived component, K_2^0, and the neutral decay mode. Similar corrections were made for the neutral decay mode of the lambda.

B. Detection of Charged *K* Mesons

As mentioned earlier, we restricted our sample of charged K mesons to include only those that decayed in the chamber. In the case of K^- mesons we also included interactions leading to hyperons which subsequently decayed in the chamber. For the evaluation of the fraction of charged-K-meson decays in the chamber, we assumed their momentum distribution to be identical to that of the neutral K mesons. Taking the chamber geometry into consideration, we arrive at a detection efficiency of $\epsilon_{K^+}=0.23$ and $\epsilon_{K^-}=0.18$. The lower K^- detection efficiency is due to the neutral and other undetectable decay modes of its interaction products.

TABLE II. Number of strange particles produced in $\bar{p}$ annihilations in propane at 1.05 Bev/c.

Particle	No. observed	ϵ[a]	α[b]	No. estimated
K^+	25 ± 1	0.23 ± 0.07	1	109 ± 40
K^-	17 ± 2	0.18 ± 0.06	1	95 ± 40
K^0 or $\bar{K}^0$	59 ± 4	0.90 ± 0.03	3	197 ± 30
Σ^+	7.5 ± 1.5	0.90 ± 0.05	2	17 ± 7
Σ^-	11.5 ± 1.5	0.90 ± 0.05	1	13 ± 4
Λ	21 ± 2	0.90 ± 0.05	1.5	35 ± 9
Total	141 ± 6			466 ± 65

[a] Here ϵ represents the efficiency for identification of the "detectable" decay mode of the particular strange particle. See text for details.
[b] Here α represents the correction factor for (a) neutral decay modes, (b) the long-lived K_2^0 mode, and (c) the $\Sigma^+ \rightarrow p+\pi^0$ decay mode.

C. Detection of Charged Hyperons

For the charged hyperons, we restricted ourselves only to the decay modes giving rise to a charged pion. For the Σ^- hyperon, the correction will thus be only due to scanning efficiency. For the Σ^+ hyperon, only the decay mode $\Sigma^+ \rightarrow \pi^+ + n$ was accepted in our sample since $\Sigma^+ \rightarrow p+\pi^0$ could not be distinguished reliably from a proton scatter.

In Table II we give a summary of the number of strange particles observed and deduced.[13] The errors quoted in column 2 are the uncertainties in identification only. Column 3 gives the efficiency for detecting strange particles in the fiducial volume of the chamber and the error associated with it. The correction factors for the neutral decay modes, the long-lived decay mode of the K^0, and in the case of the Σ^+ hyperon the correction factor for the mode $\Sigma^+ \rightarrow p+\pi^0$ are given in column 4. The last column gives the numbers of strange particles deduced. The error quoted combines the statistical error, the uncertainty in identification, and the error in the detection efficiency. Taking all these effects into account we thus find that in 3000 annihilation stars a total of 466 ± 65 strange particles were produced. These in turn correspond to 233 ± 33 stars in which a pair of strange particles occurred. This again leads to a K-meson pair-production frequency of $8\pm1\%$ for annihilation events in propane at 1.05 Bev/c. The error quoted includes the statistical error, uncertainties

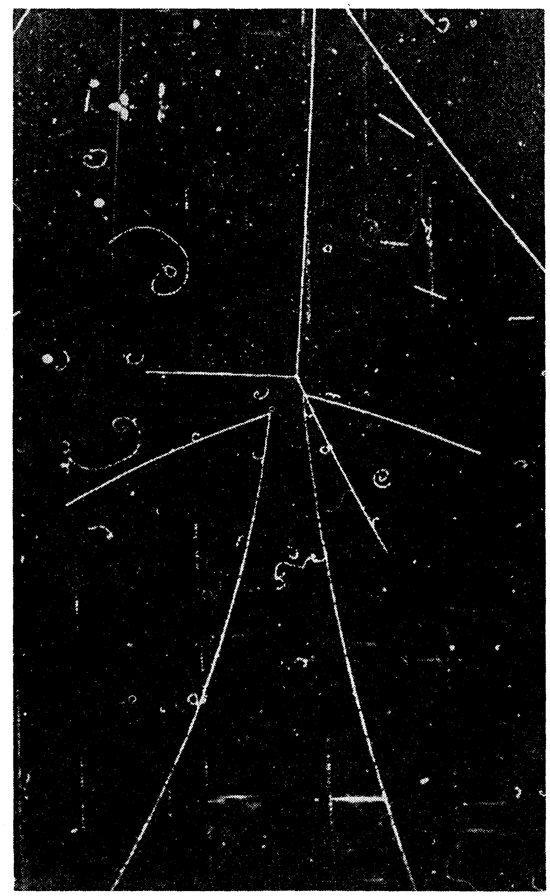

FIG. 2. Example of an $\bar{p}$ annihilation yielding two neutral K mesons. Both K^0 mesons decay near their production point and, from Q value measurements, are both identified as K_1^0 mesons.

[13] In identifying the strange particle production for $\bar{p}$ annihilation, the identity of the incoming particle must also be established. Out of the 118 stars producing identified strange particles, all except six stars had a visible energy release consistent only with an incident $\bar{p}$. The remaining six stars which gave three neutral K mesons and three hyperons could have been produced by a small admixture of K^- mesons in the beam. We shall assume that half of the six events are produced by K^- mesons.

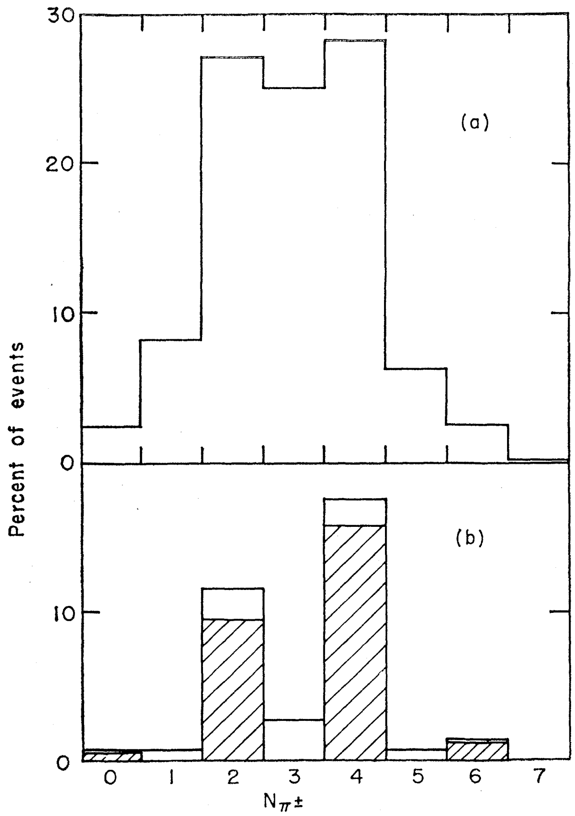

FIG. 3. (a) Observed charge-pion multiplicity distribution for $\bar{p}$ annihilation events in propane. Events with strange-particle production are omitted here, corrections have been made for π^--initiated stars which affect the results for $N_{\pi^\pm}=0$, 1, and 2, and charge-exchange events which affect the results for $N_{\pi^\pm}=0$ have been subtracted. The distribution expressed here in percentage corresponds to over 3000 events. (b) Observed charged-pion multiplicity distribution for $\bar{p}$ annihilation events without p prongs, and with $N_{\pi^-}=N_{\pi^+}$ (hydrogen-like events) or $N_{\pi^-}=N_{\pi^+}+1$. The shaded part corresponds to $\bar{p}-H$ annihilation events.

in determining the strange particles, and uncertainties associated with determining the detection efficiencies. The scanning efficiency was determined by a complete rescan of the film.

IV. STRANGE-PARTICLE PRODUCTION IN $\bar{p}p$ ANNIHILATIONS

To obtain the percentage of strange particles produced in $\bar{p}p$ annihilations, we need to determine the total number of annihilations on free hydrogen. As a first approximation, these are given by the "hydrogen-like" events. We define as "hydrogen-like" events those events for which $N_{\pi^+}=N_{\pi^-}$, and no visible knockon or evaporation protons are emitted. To find what fraction of "hydrogen-like" events corresponds to annihilation on bound protons, we examined the annihilation events with $N_{\pi^-}=N_{\pi^+}+1$ considered to be annihilations on bound neutrons. From this group we can determine the frequency of annihilation events on bound nucleons with and without accompanying proton evaporation, and hence their ratio. Applying an interpolated value of this ratio (which is a function of N_π) to the group $N_{\pi^+}=N_{\pi^-}$ with evaporation protons, we obtain the desired correction to hydrogen-like events (see Fig. 3). Namely, we estimate that 16% of the hydrogen-like events occur with bound protons, the remaining 84% correspond to true free $\bar{p}p$ annihilations. Assuming the same ratio to hold true for annihilation events yielding K particles, we deduce that K-particle production occurs in $8\pm2\%$ of all $\bar{p}p$ annihilations.

Table III gives the number of observed K mesons in hydrogen-like events and the estimated total number of K mesons produced.

V. THE PION MULTIPLICITY AND MOMENTUM SPECTRA FOR STARS WITH K MESONS

To arrive at the pion multiplicity associated with K-meson production, we restricted ourselves to a sample which excludes hyperon production. Hyperon production which is principally a consequence of $\bar{K}$ absorption in the parent nucleus would add one additional pion due to the reaction $\bar{K}+N\rightarrow\pi+Y$. Clearly a small fraction of hyperons not identified as such (neutral decay modes of Λ and $\Sigma^+\rightarrow p+\pi^0$) will still remain in the sample. This fraction, however, amounts to less than 6% of all stars producing strange particles (see Table II). We find on the average 1.8 charged particles (not counting knockon or evaporation protons) produced in association with identified K mesons. These charged particles are a mixture of pions and a small percentage of charged K mesons which were not identified as such (see Sec. III-2). Using the detection efficiencies for charged K mesons given in Table II, we deduce that the average number of charged pions associated with K mesons, $\langle N_{\pi^\pm}\rangle_K$, is 1.6 ± 0.3.[14] Assuming the number of neutral pions to be half of the charged ones, we arrive at an average pion multiplicity $\langle N_\pi\rangle_K=2.4\pm0.5$.

The momentum spectra of the pions and neutral K mesons were computed in the center-of-mass system of the annihilation and are shown in Fig. 4. To compare the experimental spectra with the statistical model, we calculated the spectra of K and π mesons for annihilations with one, two, three, and four pions produced in addition to the K pair. These calculations

TABLE III. Number of strange particles in hydrogen-like events.

Particle	No. observed	ϵ^a	α^b	No. estimated
K^+	8.5 ± 0.5	0.23 ± 0.07	1	37 ± 17
K^-	7.5 ± 0.5	0.18 ± 0.06	1	42 ± 21
K^0 or $\bar{K}^0$	23 ± 2	0.90 ± 0.03	3	77 ± 18
Total	39 ± 3			156 ± 32

[a] See note a, Table II.
[b] See note b, Table II.

[14] A correction for the absorption of pions in the parent nucleus is included in this number.

used the Lorentz-invariant phase space (LIPS) as discussed by Srivastava and Sudarshan and Desai.[15]

To fit our experimental spectra, the pion multiplicity distribution in the stars under discussion has to be determined. Experimentally this would be difficult, since our statistics do not warrant the determination of such fine detail. In the next section we discuss a modification of the statistical model which allows us, among other things, to calculate the appropriate weight factors. The calculated momentum spectrum (see Fig. 4) agrees well with the experimental data. One has to bear in mind that the experimental spectra have some momentum smear since a fraction of the annihilation stars included in the sample comes from annihilations on bound nucleons.

VI. A COMPARISON OF *K*-MESON PRODUCTION WITH STATISTICAL MODEL PREDICTIONS

In this section we investigate to what extent a further modification of the usual Fermi statistical model could explain the observed *K*-meson production and the increase of the *K*-meson production in $\bar{p}$ annihilation events with increasing $\bar{p}$ energy.

Customarily, a single parameter, the interaction volume, has been used for the calculation of both the π- and *K*-meson production. The transition probability for $n\,\pi$ and two K mesons in $\bar{p}-p$ annihilation can be written[15–17]

$$S_{n,2}=A\frac{\frac{1}{2}[g_{n,2}(1)+g_{n,2}(0)]}{n!(1!)^2}\frac{(M_K\Omega_K)^2(\mu\Omega_\pi)^n}{(2\pi)^{3(2+n)}}F_{n,2}(W_0^2).$$

Here $g_{n,2}(I)$ is the isotopic-spin weighting factor for $n\,\pi$ and two K mesons, and $F_{n,2}(W_0^2)$ is given by

$$F_{n,2}(W_0^2)=(4\pi)^n\int_\mu^{\omega_1\,\max}\int_\mu^{\omega_2\,\max}\cdots\int_\mu^{\omega_n\,\max}\prod_{i=1}^n p_i d\omega_i F_2(W_n^2),$$

where we have

$$p_i^2+\mu^2=\omega_i^2,$$

$$F_2(W_n^2)=2\pi\left(1-\frac{4M_K^2}{W_n^2}\right)^{\frac{1}{2}},$$

$$W_i^2=W_{i-1}^2-2W_{i-1}\omega_i+\mu^2,$$

and

$$\Omega_\pi=\lambda\left(\frac{4\pi}{3}\right)\left(\frac{1}{\mu^3}\right),$$

in units of $\hbar=c=1$, and

$$\omega_{i\,\max}=\frac{W_{i-1}^2+\mu^2-[(n-i)\mu+2M_K]^2}{2W_{i-1}}.$$

Here W_0 is the annihilation energy in the c.m. system, μ and M_K are the π- and *K*-meson rest masses, respectively, and p_i and ω_i are the momentum and the total energy, respectively, of the ith pion.

For $\Omega_K=(\mu/M_K)\Omega_\pi$, we get the single-parameter model; that is, $S_{n,2}$ is proportional to $(\mu\Omega_\pi)^{n+2}$. The results obtained from the above calculations which adjusted the parameter λ to fit the mean pion multiplicity failed to agree with the experimentally determined *K*-meson production for $\Omega_K=(\mu/M_K)\Omega_\pi$. In our attempt to fit the *K*-meson production, we introduced one additional parameter, $\xi=\Omega_K/\Omega_\pi$. Different coupling constants of the pion and K meson as well as the difference in their Compton wavelengths could be a theoretical justification for introducing the new parameter. It should be noted here, however, that such a treatment has to be considered as a phenomenological fit rather than a profound theory that would determine the relative strength of interactions of pions and K mesons. Similar considerations have been made by Cerulus and others.[7,18]

With this two-parameter statistical model, we calculated the increase in *K*-meson production as a function

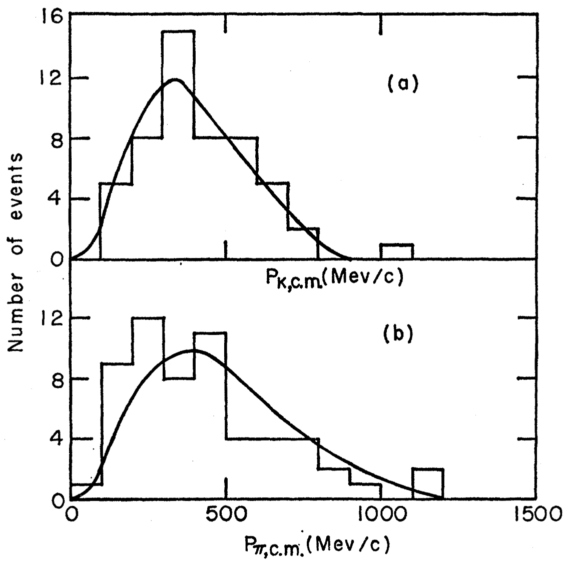

FIG. 4. (a) Histogram of the experimental neutral *K*-meson momentum spectrum in the c.m. system. (b) Histogram is the experimental charged-pion momentum spectrum (c.m.) for pions from $\bar{p}$ annihilation stars with identified *K*-meson production. The curves are obtained from the LIPS model as discussed in Sec. VI.

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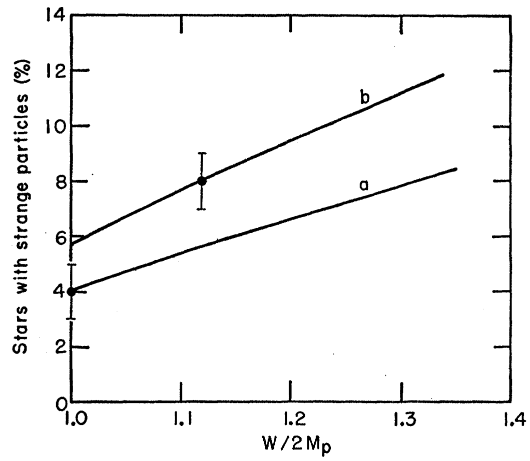

FIG. 5. Percentage of stars with strange-particle production in $\bar{p}$-annihilation events as a function of the total available energy, W, in the c.m. system. The energy, W, is expressed in units of the total available energy for annihilations at rest, viz., two times the nucleon mass. The experimental point for the annihilation at or near rest comes from references 1 through 5; the other experimental point comes from the present experiment. The curves shown are the computed variation with available energy based on the two-parameter LIPS model. Curve (a) was normalized to the experimental results for annihilations at rest, and curve (b), to the results of the present experiment. As can be noted, only in the extreme case of about one standard deviation on each of these experiments will a single curve fit both experimental points. The calculations have been extended to a value of $W/2M_p=1.34$, which corresponds to a $\bar{p}$ lab momentum of 2.23 Bev/c.

of the annihilation energy. The results of these calculations are summarized in Figs. 5 and 6 and Table IV. Here Ω_π was adjusted to obtain $\langle N_\pi\rangle=4.9$ for annihilations at rest and Ω_K was adjusted to obtain 4% K-meson production for annihilations at rest (Fig. 5, curve a). Curve b is normalized to 8% K-meson production at 1.05 Bev/c to fit the present experiment. This was done by setting $\Omega_\pi=8\Omega_\pi{}^0$ and $\xi=0.10$ and 0.12, respectively. Figure 6 gives the average number of pions associated with K mesons as a function of $\bar{p}$ energy. The corresponding pion multiplicity distributions are given in Table IV.

We also calculated K-meson production and the $\langle N_\pi\rangle_K$ value for $\bar{p}$ annihilations in carbon, and found no significant differences from $\bar{p}-$H annihilation.

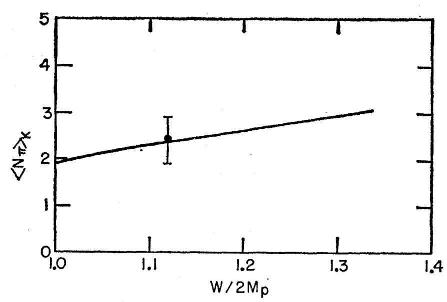

FIG. 6. Average pion multiplicity for annihilation events with associated K-meson production. The experimental point comes from the present experiment. The curve that shows the variation with $W/2M_p$ was calculated as discussed in the text.

We note that the statistical model leads to an increase in the π-meson multiplicity in annihilation events where K mesons are produced. At our energy, $W_0=2.1$ Bev, the predicted value of $\langle N_\pi\rangle_K=2.4$ is in good agreement with our experimental value of 2.4 ± 0.5. The data on $\langle N_\pi\rangle_K$ for annihilations at rest are statistically poor, but they are consistent with the calculated value.[5] The expected increase in $\langle N_\pi\rangle_K$ with increasing annihilation energy will have to be verified by future experiments.

A comparison of the calculated K-meson-production increase with the experimental data shows, however, that only in the limits of the rms errors quoted can we get agreement with our calculation. It is clear that until we solve our fundamental difficulty in calculating the pion multiplicity with a reasonable interaction volume, all attempts to fit K-meson production are of a very preliminary nature.

VII. ANNIHILATION STARS WITHOUT K-MESON PRODUCTION

A number of attempts have been made to explain the large pion multiplicity associated with annihilation events at rest and low energy. As mentioned in Sec. I, these attempts must be classified as phenomenological since they all adjust some of the parameters to fit the observed average pion multiplicity. It was hoped that by examining the pion multiplicity as a function of the total energy available to the system, some light might be shed on this intricate process.

TABLE IV. Computed pion multiplicity distribution for $\bar{p}$ annihilation stars with K meson production.[a] These values were computed on a two-volume parameter Lorentz-invariant statistical model.

$P_{\bar{p}}$ (Bev/c)	% stars with two K and 0π	1π	2π	3π	4π
0	1	25	55	18	1
1.05	0	11	46	37	6

[a] Production of five pions has been neglected.

We determined the average pion multiplicity from direct observation of the charged pions and from electron pairs produced by the decay γ rays of the neutral pions. The average mean free path for conversion was evaluated, taking proper account of the energy dependence of γ-ray conversion. Therefore, we evaluated the neutral pions for each charged-pion multiplicity separately in order to properly account for the variation of the energy spectra as a function of pion multiplicity (see Table V).[19]

[19] An independent measure of the neutral-pion multiplicity was obtained from the Dalitz pairs emitted in the annihilation events. This method gives a lower limit, because not all Dalitz pairs can be uniquely identified. A total of 70 Dalitz pairs were observed which give a lower limit of $\langle N_{\pi^0}\rangle\gtrsim1.4\pm0.2$.

TABLE V. The neutral-pion multiplicity as a function of the charged-pion multiplicity for $\bar{p}$ annihilation events.

	Neutral pions per star	
$N_{\pi^\pm}$ observed	Hydrogen-like events	Carbon events
0	a	$2.9^{+3.0}_{-0.9}$
1		2.0 ± 0.4
2	2.5 ± 0.5	2.1 ± 0.2
3		1.4 ± 0.1
4	1.1 ± 0.1	1.0 ± 0.1
5		0.8 ± 0.1
6	08 ± 0.4	0.7 ± 0.3
7		1.0 ± 0.8

[a] The neutral-pion multiplicity for $N_{\pi\pm}=0$; "hydrogen-like" events could not be determined.

We find the average pion multiplicity to be essentially the same for carbon and hydrogen events, i.e., $\langle N_\pi\rangle = 5.0\pm0.2$. Details of the various contributions to the pion multiplicity are given in Table VI.

A. Variation of Pion Multiplicity and Momentum Spectra with $\bar{p}$ Momentum

As the $\bar{p}$ momentum increases, the additional available energy may either go into the production of a larger number of pions or into an increase of the pion momenta. The former will increase the average pion multiplicity, the latter the average pion momentum. A correct model of the annihilation process will also have to give the proper behavior for the change in pion multiplicity with $\bar{p}$ momentum. It appears to us that with a sufficient increase in $\bar{p}$ momentum this approach may shed more light on the annihilation process. In the present experiment we do not find an appreciable increase in the pion multiplicity (within our statistics) over the annihilation stars occurring at rest. For the latter we consider 4.9 ± 0.2 as an average pion multiplicity, taking into account all the low-energy experiments.[1–5] On the basis of the LIPS model with $\Omega_\pi=8\Omega_\pi{}^0$, a larger increase in $\langle N_\pi\rangle$ would have been expected [see curve (a), Fig. 7]. Curve (b) in Fig. 7 is a variation of the LIPS model which takes into account the Lorentz contraction of the interaction volume as first suggested in Fermi's original paper,[20] i.e., $\Omega=8\Omega^0\times(2M/W)$. Curve (c) shows the variation in pion multiplicity as computed from the Koba-Takeda model.[8] As can be seen from Fig. 7, which also shows our experimental point, one cannot choose conclusively between these models from the present data. However, at momenta of about 3 Bev/c, the differences become very marked.

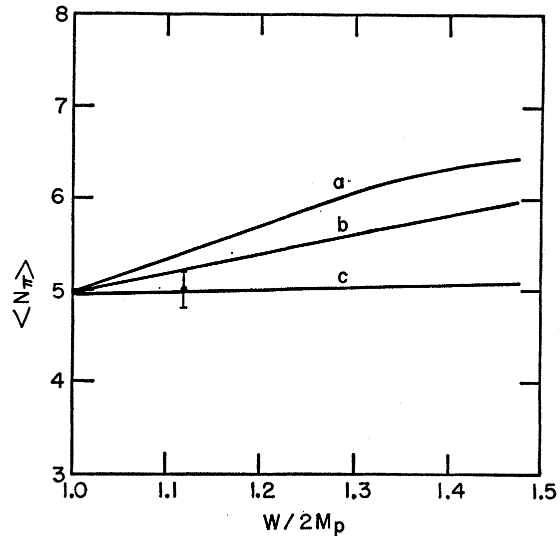

FIG. 7. The variation of the average pion multiplicity in $\bar{p}$ annihilation stars (excluding K-meson-production events) with $W/2M_p$. The experimental point comes from the present experiment. All computed curves have been normalized to an average pion multiplicity of 4.9 for annihilations at rest. This gives a volume $\Omega=8\Omega_0$ in the LIPS calculation. Curve (a) corresponds directly to that volume. Curve (b) corresponds to the same model with the inclusion of a Lorentz contraction of the annihilation volume. Curve (c) corresponds to the Koba-Takeda model, also normalized to an average multiplicity of 4.9 for annihilations at rest.

Figures 8 and 9 show the c.m. momentum spectra for hydrogen-like events for $N_{\pi^\pm}=4$ and $N_{\pi^\pm}=6$. The average c.m. total energies for these samples are $E_4=410\pm10$ Mev and $E_6=323\pm15$ Mev, respectively, which show an increase over the corresponding total energies for annihilations at $\langle T_{\bar{p}}\rangle=50$ Mev, namely

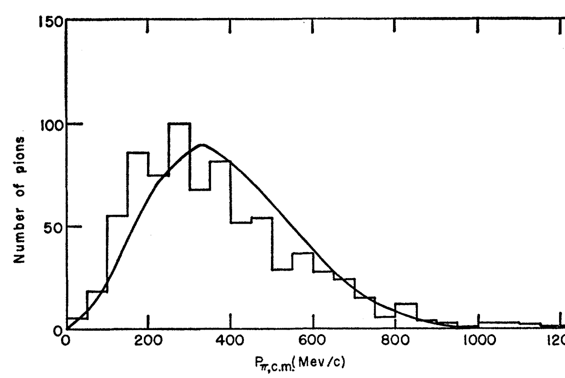

FIG. 8. The pion momentum spectrum in the c.m. system for hydrogen-like annihilation stars with $N_{\pi^\pm}=4$. The curve corresponds to a calculation with $\Omega=8\Omega_0$.

TABLE VI. The determination of the average pion multiplicity.

Pion type	Hydrogen-like events	Carbon events	Source
$\langle N_{\pi^\pm}\rangle$	$3.3\ \pm0.15$	$2.6\ \pm0.10$	Direct observation
$\langle N_{\pi^0}\rangle$	1.65 ± 0.15	1.55 ± 0.10	From conversion γ rays
Absorbed pions		$0.9\ \pm0.15$	From nuclear excitation in carbon
$\langle N_\pi\rangle$	4.95 ± 0.2	5.05 ± 0.2	Average for propane: 5.0 ± 0.2

[20] E. Fermi, Progr. Theoret. Phys. (Kyoto) 5, 570 (1950).

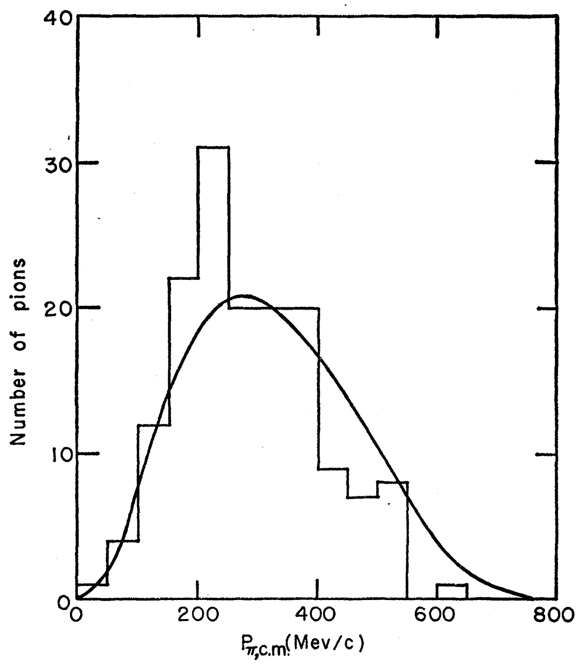

FIG. 9. The c.m. momentum spectrum for hydrogen-like annihilation events for $N_{\pi^\pm}=6$. The curve was computed with $\Omega=8\Omega_0$.

$E_4=365\pm20$ Mev and $E_6=295\pm40$ Mev (the latter values were obtained by combining the results of references 3 and 5). This is in accord with the fact that the multiplicity has not changed appreciably. Also shown in Figs. 8 and 9 are the computed momentum spectra for $\Omega=8\Omega^0$.

B. Two-Pion Annihilations

A search was made among the hydrogen-like events for the pure two-pion type annihilation events:

$$\bar{p}+p\rightarrow\pi^++\pi^-.$$

For this purpose all two-prong events that could be considered of the above type were measured (i.e. events with associated converted γ rays were not considered). No event was found to correspond to this reaction and, at most, one event could have been consistent with it. To qualify as a significant measurement, each outgoing pion track had to be longer than 8 cm. The "one event" thus corresponds not to all "hydrogen-like" events but rather to a smaller sample of about 500 events.

VIII. CROSS-SECTION MEASUREMENTS

A. Annihilation Cross Section

For all cross-section determination we have restricted ourselves to a central region of the chamber and have applied strict angular entrance criteria of ±5 deg. Within this region we have observed 3385 ± 550 m of $\bar{p}$ path length and 2900 ± 120 annihilation stars. The latter can be further separated into 780 ± 60 annihilation events in hydrogen and 2120 ± 100 annihilation events in carbon, as described in Sec. IV. We thus obtain the following annihilation cross sections at $P_{\bar{p}}=1.05$ Bev/c:

$$\sigma_{\bar{p}p}(\text{annihilation})=51\pm10 \text{ mb},$$
$$\sigma_{\bar{p}C}(\text{annihilation})=368\pm60 \text{ mb}.$$

B. Charge-Exchange Cross Section

The antiproton charge-exchange reaction $\bar{p}+p\rightarrow\bar{n}+n$ can be identified reliably in this experiment only by observing the disappearance of a $\bar{p}$ and the subsequent annihilation of the $\bar{n}$. We have observed 24 such events. Here the criterion for $\bar{n}$ annihilation was that three or more mesons be emitted in the process. In all, we have observed 109 ± 30 $\bar{p}$ disappearances (this number is already corrected for pion contamination). From the above data, we can estimate the $\bar{p}$ charge-exchange mean free path in propane in the following manner: (a) We assume that the mean free path for $\bar{n}$ annihilation is the same as for $\bar{p}$ annihilation. (b) Taking into account the geometry of the chamber, we find that 90 ± 30 of the disappearances must be ascribed to charge-exchange events. This yields a mean free path of 38 ± 14 meters for the charge-exchange reaction in propane. It should be noted here that of the 24 $\bar{n}$ annihilations observed, none originated from a source that exhibited nuclear excitation. This observation together with the fact noted elsewhere that the charge-exchange reaction is small in complex nuclei[21] leads us to believe that the majority of the events are charge-exchange reactions occurring on hydrogen. In Fig. 10 we give the observed angular distribution of the charge-exchange events. A very strong forward peaking is

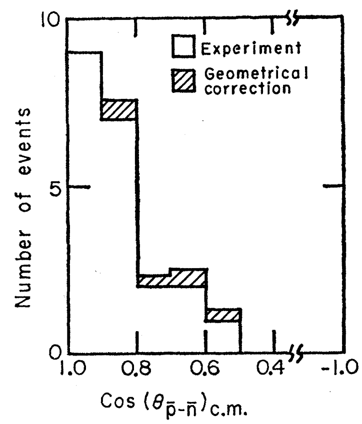

FIG. 10. The angular distribution of the 24 observed $\bar{p}$ charge-exchange events. No event was observed with c.m. angle greater than 60 deg. The shaded region shows the correction for the geometry of the chamber. The geometrical corrections increased somewhat with increasing angle; however, the absence of charge-exchange events at angles greater than 60 deg cannot be ascribed to geometrical effect. The distribution is thus very strongly forward-peaked.

[21] R. C. Weingart, thesis, University of California Radiation Laboratory Report UCRL-8025, October 18, 1957 (unpublished).

observed in this distribution. Qualitatively this can be understood if we consider that collisions with small momentum transfers, i.e., large impact parameters, can lead to charge exchange, while the large-momentum-transfer collisions lead principally to annihilations.

A small forward peaking in the $\bar{p}-p$ charge-exchange differential cross section is predicted by Ball and Fulco at 750 Mev/c.[22] They predict also a second peak at 180 deg in the c.m. system. However, our results which show a more pronounced forward peaking cannot be compared directly with their predictions, since the approximation methods used by these authors break down at higher antiproton momenta.

IX. PION PRODUCTION BY INELASTIC SCATTERING OF ANTIPROTONS

In this experiment we observed a number of examples of single-pion production and one instance of double-charged pion production by inelastic scattering of antiprotons. We were severely hampered in the quantitative evaluation of these data because of the very limited statistics, viz., eight identified single-pion production events. For the identification of such an event, we required (a) identification of the pion (which is highly efficient for charged pions) and (b) identification of the $\bar{p}$ which entailed a subsequent annihilation in the chamber. Of the inelastically scattered protons, 4 ± 1 annihilated "at rest" and four in flight. The detection efficiency is based on the estimate that 0.20 ± 0.05 of all the inelastically scattered antiprotons will annihilate in flight in the chamber. The fraction coming to rest and annihilating was estimated from the three-particle phase space. The detection efficiency for neutral pions by γ-ray conversion in the chamber is $\sim$0.15. Details on the events observed and on the detection efficiency are given in Table VII. We have not observed any examples of charge-exchange events with inelastic pion production.

[22] J. S. Ball and J. R. Fulco, Phys. Rev. **113**, 647 (1959).

TABLE VII. Pion-production events by inelastic scattering of antiprotons.

Reaction	No. events identified	Detection efficiency
$\bar{p}+p\rightarrow\pi^{+}+\bar{p}+n$	4	$0.4\ \pm0.1$
$\bar{p}+p\rightarrow\pi^{0}+\bar{p}+p$	1	0.06 ± 0.02
$\bar{p}+n\rightarrow\pi^{-}+\bar{p}+p$	2	$0.4\ \pm0.1$
$\bar{p}+n\rightarrow\pi^{0}+\bar{p}+n$	1	0.06 ± 0.02
$\bar{p}+n\rightarrow\pi^{+}+\pi^{-}+\bar{p}+n$	1	

We thus estimate that inelastic $\bar{p}$ scattering in propane with charged-pion production occurs with a frequency of $0.4\pm0.3\%$ of the annihilation process. If we ascribe all the observed π^{+} production ("hydrogen-like") events to annihilations with free protons, we get an estimated upper limit for this cross section of $\sigma(\bar{p}+p\rightarrow\bar{p}+\pi^{+}+n)\leq0.5\pm0.3$ mb.

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FIG. 1. Example of an $\bar{p}$ annihilation event yielding two charged K mesons. The reaction observed is $\bar{p}+``p" \rightarrow K^{+}+K^{-}+\pi^{+}+\pi^{-}+n\pi^{0}$. The K^{+} meson decays in the τ mode, giving $\pi^{+}+\pi^{+}+\pi^{-}$. The π^{+} mesons in turn show the characteristic $\pi^{+}\rightarrow\mu^{+}\rightarrow e^{+}$ decay. The K^{-} meson interacts in carbon (noncoplanar) giving a Σ^{+} and π^{-}. The Σ^{+} decays *via* the $\pi^{+}+n$ mode.

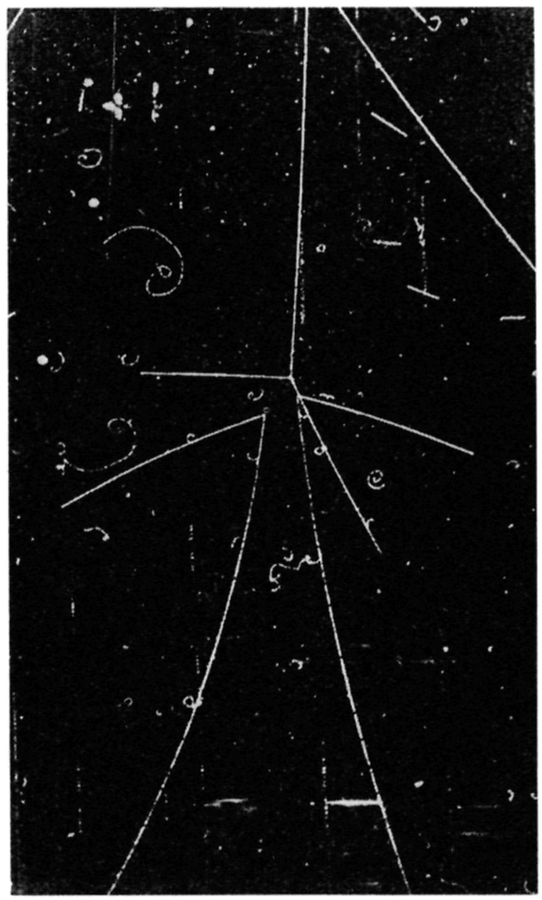

FIG. 2. Example of an $\bar{p}$ annihilation yielding two neutral K mesons. Both K^0 mesons decay near their production point and, from Q value measurements, are both identified as $K_1{}^0$ mesons.