6000 K_σ^- events (K^- capture stars at rest, giving rise to at least one secondary particle) is shown in Fig. 1. The main body of the K^- beam ($\sim$99%) indeed stops at the expected position (corresponding to an entrance momentum of 300±10 Mev/c), with a tail in both the high- and low-range sides. All the particles having a range less than 25 mm were more critically examined. Entering pions (13 events) and protons (1 event) were immediately removed from the analysis. On all the rest of the short-range tracks (see Fig. 1), careful ionization measurements were performed, using as reference tracks K^- mesons from the main body of the K^- beam. The measurements showed that all the short-range tracks were due to ordinary K^- mesons. Again, nothing unusual was observed.

In conclusion, we wish to give the upper limit for the frequency of occurrence of the D^- meson obtained in the present work, under the experimental conditions as described in reference 4. From the search for double strangeness release, the upper limit is about 1% (since the probability for single Σ or hyperfragment observation in K^- capture is about 10%). From the direct mass measurement, however, the upper limit is $\sim$1/6000.

ACKNOWLEDGMENTS

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Internal Pairs Following π^- Capture in Hydrogen*

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Internal electron pairs from the two reactions (1) $\pi^-+p\rightarrow n+\pi^0\rightarrow n+\gamma+e^++e^-$ and (2) $\pi^-+p\rightarrow n+e^++e^-$ have been studied in a hydrogen bubble chamber. 2184 cases were seen. A geometrical cutoff selected 1523 of these as suitable for momentum measurement. By an analysis of the momentum spectrum, the Panofsky ratio was measured to be 1.51±0.10. The total intensity, momentum partition within the pairs, and distribution in virtual photon mass are in essential agreement with the theoretical predictions of Kroll and Wada as recently extended by Joseph.

INTRODUCTION

The original experiment on the absorption of negative pions by hydrogen[1] provided several results which were crucial to pion physics. When a negative pion comes to rest in liquid hydrogen it is captured into a mesonic hydrogen atom and absorbed from an s state[2] by the proton. The time from atomic capture to nuclear absorption is about 10^{-12} sec [2,3] which is very much shorter than the decay time of 2.5×10^{-8} sec, so almost all the mesons are absorbed. This absorption was shown experimentally to lead to two reactions:

$$\pi^-+p\rightarrow n+\pi^0, \quad (1)$$

$$\pi^-+p\rightarrow n+\gamma. \quad (2)$$

The ratio between the rates of these two reactions,

$$P=w(\pi^-+p\rightarrow n+\pi^0)/w(\pi^-+p\rightarrow n+\gamma),$$

which is now called the Panofsky ratio, was measured to be 0.94±0.3. Since this ratio provides a link between the zero-energy charge-exchange scattering and photoproduction of π mesons,[4,5] several later and better measurements have been made. These are summarized in Table I.[1,6–9]

The results do not seem statistically compatible. All of the experiments in Table I were performed with

Table I. Results of previous measurements of the Panofsky ratio.

Author	Result
Panofsky *et al.*, reference 1	0.94±0.3
Cassels *et al.*, reference 6	1.50±0.15
Kuehner *et al.*, reference 7	1.60±0.17
Fisher *et al.*, reference 8	1.87±0.10
Koller *et al.*, reference 9	1.46±0.10

* This work was supported in part by the U. S. Atomic Energy Commission.
[1] W. K. H. Panofsky, R. L. Aamodt, and J. Hadley, Phys. Rev. **81**, 565 (1951).
[2] T. Day, G. A. Snow, and J. Sucher, Phys. Rev. Letters **3**, 61 (1959).
[3] T. H. Fields, G. B. Yodh, M. Derrick, and J. G. Fetkovich, Bull. Am. Phys. Soc. **4**, 402 (1959). Further results will be published shortly.
[4] H. L. Anderson and E. Fermi, Phys. Rev. **86**, 794 (1952).
[5] J. Hamilton and W. S. Woolcock, Phys. Rev. **118**, 291 (1960). This paper gives references to other papers on the subject.
[6] J. M. Cassels, G. Fidecaro, A. M. Wetherell, and J. Wormold, Proc. Phys. Soc. (London) **A70**, 405 (1957).
[7] J. A. Kuehner, A. W. Merrison, and S. Tornabene, Proc. Phys. Soc. (London) **73**, 545 (1959).
[8] J. Fisher, R. March, and L. Marshall, Phys. Rev. **109**, 533 (1958).
[9] E. L. Koller and A. M. Sachs, Phys. Rev. **116**, 760 (1959).

counter techniques so a measurement using a bubble chamber was undertaken.[10]

Dalitz[11] pointed out a possible alternative decay made of the π^0 meson,

$$\pi^0 \to \gamma + e^+ + e^-,$$

and calculated the internal conversion probability

$$2\rho_{\pi^0} = (\pi^0 \to \gamma + e^+ + e^-)/(\pi^0 \to \gamma + \gamma).$$

Kroll and Wada[12] extended this to the second reaction and calculated the internal conversion probability of the γ ray,

$$\rho_\gamma = (\pi^- + p \to n + e^+ + e^-)/(\pi^- + p \to n + \gamma).$$

Such electron pairs were seen in a diffusion cloud chamber.[13] A more detailed theoretical investigation of the processes involved has recently been made by Joseph,[14] who obtained

$$\rho_\gamma / 2\rho_{\pi^0} = 0.00710/0.01196 = 0.594.$$

This experiment consists of a bubble chamber study of these electron pairs.

APPARATUS AND PROCEDURE

A 6-in. diameter bubble chamber in a 9460-gauss field was used to stop π^- mesons from the Carnegie Institute of Technology synchrocyclotron. A 120-Mev π^- beam impinged on a 2-in. copper absorber fastened on the outside of the chamber. About 15% of the pions in the beam stopped inside the chamber, yielding about 12 stopping π^- in the liquid per picture, with an equal number going into the glass windows. Figure 1 shows one of the pictures.

The film was scanned by projecting the two views on a translucent screen at about twice life size. Electron pairs were scanned for by looking first for tracks curving in the opposite sense from the beam curvature and secondly for all tracks making a large angle with the beam direction. Each such track was traced back to its point of origin and the second track searched for. Then an area scan was made looking at all the π^- endings. All the events reported were examined by a physicist and classified. Events were accepted as internal pairs if the secondary tracks seemed to be minimum ionizing and came from the end of what appeared to be a stopping π^- track. The entrance position and angle of the π^- track were suitably restricted. All such events were sketched on sheets which were used by the measurer to locate the event. All the 24 719 frames used were scanned twice by two independent scanners, and on 13 251 of these frames a third independent scan was made by the two scanners with highest scanning efficiency.

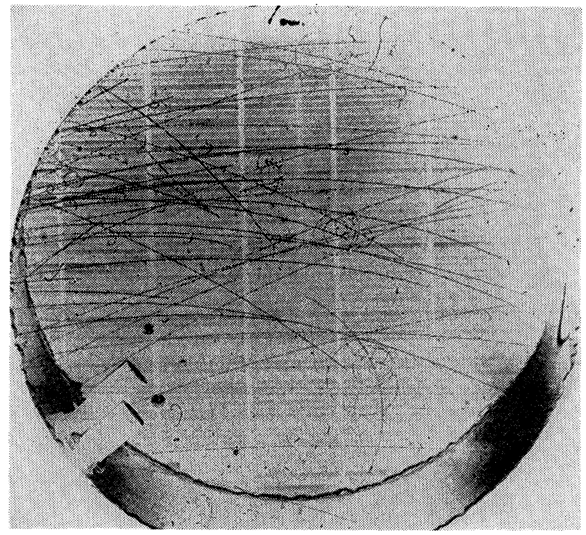

FIG. 1. One view of the stopping pion beam, showing an electron pair.

Each event was measured on a machine which punched out the Cartesian coordinates of any point on the picture when set in coincidence with a fixed mark.[15,16] The common point of the pair and four other points along each electron track were measured on each view together with three fiducial marks.

The space angles and momentum of each track were calculated on an IBM 650 computer. The computer program was based on an iterative procedure wherein an orbit in the chamber was constructed which duplicated the observed film initial angles and average curvatures. The calculation, which took 3.5 minutes for each electron pair, allowed for energy loss of the electron in the liquid hydrogen.

RESULTS

1. Total Conversion Rate

The total number of electron pairs per stopped pion has been measured by counting the number of stopping pions. 78 random frames were taken and all the stopping pion tracks, satisfying the same entrance criteria as used for the pions giving electrons pairs, were counted and paired off on the two views. The end points of these tracks were measured and their spatial distribution calculated. The depth distribution of the stops and the events are shown in Fig. 2. There is some indication of loss of events near the windows, which is not surprising since immediately at the window, for example, only one half of the events can be seen. In

[10] M. Derrick, J. G. Fetkovich, T. H. Fields, and J. Deahl, Bull. Am. Phys. Soc. 4, 401 (1959).
[11] R. H. Dalitz, Proc. Phys. Soc. (London) **A64**, 667 (1951).
[12] N. M. Kroll and W. Wada, Phys. Rev. **98**, 1355 (1955).
[13] C. P. Sargent, R. Cornelius, M. Reinhart, L. M. Lederman, and K. Rogers, Phys. Rev. **98**, 1349 (1955).
[14] D. W. Joseph, Nuovo cimento (to be published).
[15] M. Derrick, T. H. Fields, and R. W. Findley, *Proceedings of the International Conference on High-Energy Accelerators and Instrumentation, CERN, 1959* (European Organization for Nuclear Research, Geneva, 1959), p. 557.
[16] T. H. Fields and R.W. Findley (to be published).

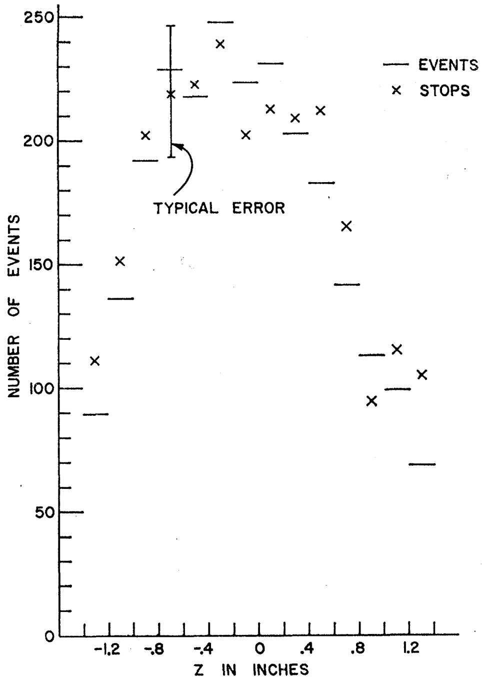

FIG. 2. Depth distribution of the vertex of the events and stops. The chamber windows are at ±1.5 in. A cutoff at ±1.4 in. was imposed.

the other two directions the stops and events have distributions in agreement. For the conversion rate the central region of the chamber, $|x|\leqslant 2$ in., $|y|\leqslant 2$ in., and $|z|\leqslant 1$ in. was taken. On the events in this box a further check has been made by plotting their angular distribution. They should be isotropically distributed. The space angles used are those of the bisector of the initial directions of the two tracks. Figure 3 shows the distribution in ϕ and Fig. 4 the distribution in α, where ϕ and α are the azimuthal and polar angles with respect to the magnetic field direction. The agreement with isotropic emission is satisfactory, indicating no serious systematic loss of events.

All these plots have the events found in the third scan included but multiplied by 1.86 to correct for the frames which were not scanned a third time. The total number of events involved is given in Table II.

The conversion probability can now be calculated. It depends weakly on the Panofsky ratio. Assuming 1.50 for this and assuming that all stopped pions undergo either reaction 1 or reaction 2 and then using

TABLE II. Number of events found in scanning.

Number of events found on first two scans	=1955
Number of events found on third scan of part of film	=229
Expected number of events for third scan of rest of film	=229×0.86=197
Total events on film	=2381

Joseph's[14] results, 1.0016% of the stopping pions should give a pair. The results obtained are summarized in Table III.

A possible loss of pions by capture on impurities was investigated by scanning 1000 pictures for stars which would be made by such absorptions. The results indicate that a maximum of 0.5% of the stopping mesons were captured on impurity, which is a negligible fraction. The impurity may have been helium remaining from leak-testing the chamber prior to initial filling with hydrogen.[17]

Another error in the count of stopping pions can arise from muons stopping in the chamber and undergoing nuclear absorption on an impurity. The probability of transfer to an impurity is much larger for muons than pions because of the longer lifetime. A scan for $\mu-e$ decays indicates that $(2.0\pm0.5)\%$ of the

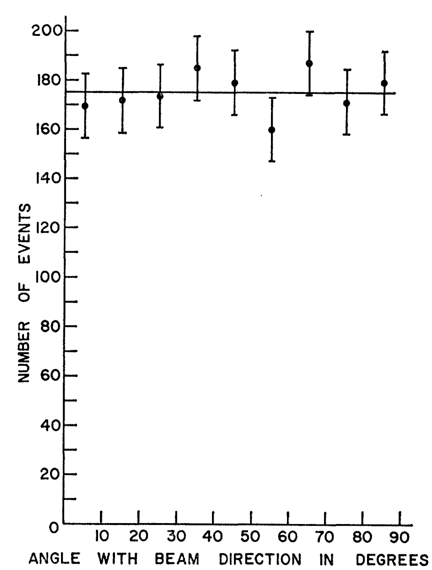

FIG. 3. Distribution in azimuthal angle, ϕ. The four quadrants have been folded over into one.

stopping tracks were muons. Since a maximum of about 10% of these suffer nuclear absorption the correction is negligible.[18]

The results listed in Table III show that the observed number of pairs was less by $(7\pm7)\%$ than the predicted number.

2. Double Pairs

For a small fraction of the π^0 mesons created by reaction (1) both decay γ rays should internally convert. The rate of double decay should be 2.94×10^{-3} times the single rate.[12] From the number of cases of single decay, four examples of the double decay should have

[17] A more extended study of π^- captures in hydrogen helium mixtures is being made and will be published later.

[18] The 10% fraction we estimate from other experience with stopping muons in bubble chamber hydrogen.

been seen. Three were observed. A more extended study of such double pairs has been reported previously by the Columbia group.[19]

3. Panofsky Ratio

To select events for use in the determination of the Panofsky ratio, a geometrical cutoff was made using both the direction of the bisector of the two tracks of the pair and the location of the vertex. This gives a criterion for the measurability of an event since the pairs usually have a small opening angle, and yet does not bias the event selection. The bisector was projected until it intersected the chamber wall and the projection of this distance on the glass window taken as a measure of the precision to be expected because of the track length. This was multiplied by a function of the space angles, which gave the error to be expected in α, the angle with the magnetic field direction. (For events

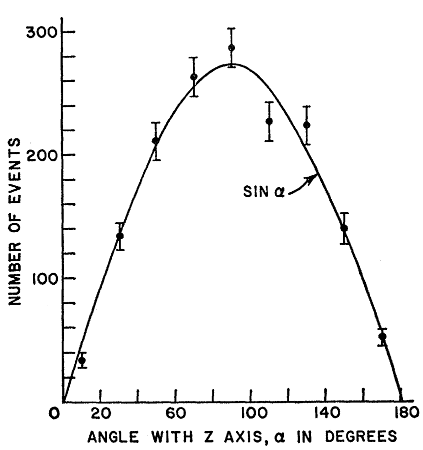

FIG. 4. Distribution in polar angle, α. Very steep events with short projected lengths occur near 0° and 180°.

near the plane defined by the two camera lenses and the center of the chamber the error in α predominates.) The resulting number was called the precision parameter. The energy spectrum was examined as a function of this precision parameter and an arbitrary cutoff decided on to minimize the total error. The spectrum corresponding to this cutoff is shown in Fig. 5. As the precision parameter is reduced the spectrum improves, with a smaller fraction of the events in the valley between the two peaks, but the statistical error becomes larger. An experimental check on the constancy of the Panofsky ratio for different precision parameters was made, and no bias was evident within the statistical accuracy.

The energy resolution was not good enough to separate cleanly the two kinds of event so a calculated spectrum has been fitted in order to estimate the

TABLE III. Results of stop count and calculation of number of events expected in central volume of chamber.[a]

Number of frames scanned	= 24 719
Mean number of pion stops in the central volume per frame	= 6.99±0.34
Total number of pion stops in central volume	=172 786±8404
Number of pairs expected	= 1728±84
Number of pairs found in the central volume	= 1636±54
Number of pairs found, corrected for external pairs and charge exchange scattering in flight	= 1618±55

[a] The observed number of stops and pairs include an upward correction of 2±2% to allow for scanning inefficiencies.

contribution from each reaction. Since the high-energy peak corresponds to an almost unique energy it was fitted first. Several effects broaden the line, the two most important coming from multiple scattering of the electron by the liquid hydrogen and the error in measuring the curvature of the track on the film. For high-energy tracks with a small sagitta the measuring error is more important while for low energies multiple scattering predominates. These two errors were combined and summed over the experimental track length distribution in the chamber. A further sum was made over the energy distribution between the electrons in the pair assuming all fractions equally likely. The resulting spectrum was then corrected for radiative energy loss using the Bethe-Heitler theory.[20] The final curve is shown in Fig. 5 normalized to the same total number of events as the experimental points for the high-energy half of the curve. The same constants were then used to fit the π^0 curve for different values of the

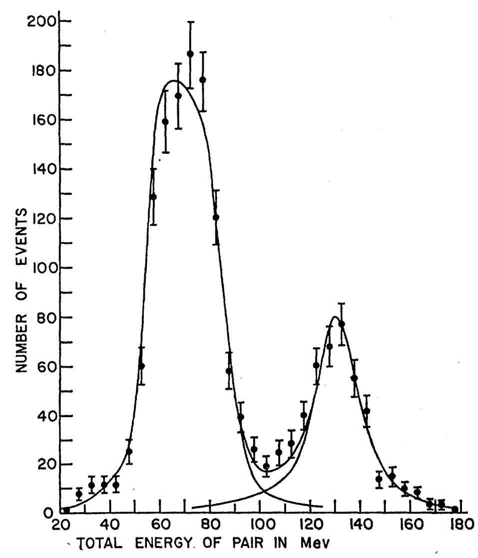

FIG. 5. Total energy spectrum of pairs. The curves are theoretical, with the experimental energy resolution folded in.

[19] R. Plano, A. Prodell, N. Samios, M. Schwartz, and J. Steinberger, Phys. Rev. Letters 3, 525 (1959).

[20] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1954), 3rd ed., p. 377ff.

TABLE IV. Number of events found, after selection by precision parameter and classification as π^0 event, total energy$<$100 Mev or γ event, total energy$>$100 Mev.

	π^0	γ
Number of events found in first two scans	954±31	396±20
Number of events found in third scan	132±12	41±64
Calculated number of events on rest of film which were not found	113±10	35±5.2
Total events	1199	472
Corrected events	1191±37	468±23

$\pi^- - \pi^0$ mass difference. The one shown gave the best fit and corresponds to a mass difference of 8.8 electron masses. This mass difference agrees within its error of about 0.6 m_e with a more accurate measurement[21] which gave 8.991±0.020 electron masses. The upper curve between the two peaks is the sum of the π^0 and γ curves and makes a satisfactory fit to the points in the valley. A cutoff energy of 100 Mev was chosen to make the area under the two tails in the overlapping region the same. All events with energy less than this were considered to come from the π^0 reaction and rest from the γ reaction.

Two small sources of background must be corrected for. A few external pairs are created very close ($<$0.1 cm) to the end of a pion track so that they look like internal pairs. This gives 7 π^0 pairs and 5 γ pairs. The second source of background is provided by charge-exchange scatterings in flight followed by the Dalitz decay of the π^0. This provides an extra 5 low-energy pairs and 1 high-energy pair. Multiplying these numbers by the ratio of events used to all events present, which is 0.69, gives 8 π^0 and 4 γ events to subtract.

Finally, there are 1191 π^0 events and 468 γ events:

$$\text{Panofsky ratio} = (1191/468)\times 0.594 = 1.51\pm 0.10.$$

The statistical error on the high-energy events is 5% and for the low-energy ones 3%. An uncertainty in the exact cutoff energy introduces a 2% error. The statistical errors include the fact that not all the film was scanned three times so the actual number of events found are not those given above. The data are summarized in Table IV. In addition a 3% systematic error has been included to account for a possible loss of events as discussed in the next section. (This measurement of the Panofsky ratio depends on the correctness of *ratio* of the two theoretical conversion probabilities. Assuming this ratio, then the results on the total conversion rate checks the common scale factor of the theoretical conversion probabilities.) Recently, a value of $P=1.62\pm 0.06$ has been obtained by Samios using this same method.[22,23]

A value of $P=1.5\pm 0.1$ was used by Hamilton and Woolcock[5] in a recent discussion of low-energy pion phenomena. They found good agreement between the low-energy s-wave phase shifts calculated from photoproduction experiments by means of the Panofsky ratio and the direct measurements from scattering experiments.

4. Internal Pair Production

The theory of internal pair creation by the processes observed here has been studied by several authors.[11,12,14] The most detailed study, in which several second-order corrections coming from finite size and magnetic moment effects of the proton and the contribution from

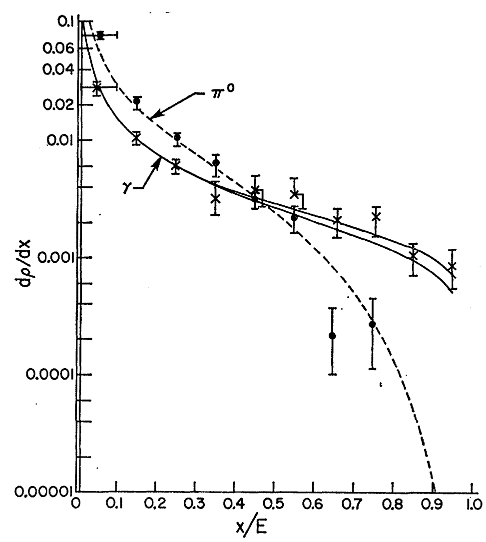

FIG. 6. Distribution of pairs in virtual photon mass. The curves are those calculated by Joseph (reference 14). Both curves fall to zero at $x/E\sim 0.007$. The lower full curve is the contribution from transverse photons only; the upper full curve includes proton magnetic moment and size effects and the longitudinal photon contribution. Both the dotted and upper full curve have radiative corrections included. The full curves and × experimental points are for the γ reaction. The dotted curve and ● experimental points are for the π^0 reaction.

longitudinal photons (for the γ-ray reaction) have been considered, is that of Joseph.[14] Since the photon which gives rise to the pairs is virtual it can have a nonzero mass. The calculation of the conversion probability is carried out in terms of this mass, as measured by the four-momentum of the electron pair:

$$x^2 = k_0^2 - k^2,$$

where k_0 = total energy of electron pair, k = total vector momentum of electron pair. This can be approximated, by neglecting the rest mass of the electrons compared to their kinetic energy, as

$$x^2 = (2k_+)(k_-)(1-\cos\theta),$$

where k_+, k_- = momentum of positron and electron, θ = opening angle between electrons.

[21] R. P. Haddock, A. Abashian, K. M. Crowe, and J. B. Czirr, Phys. Rev. Letters **3**, 478 (1959). This paper gives references to other accurate measurements of the $\pi^- - \pi^0$ mass difference.

[22] N. P. Samios, Bull. Am. Phys. Soc. **5**, 71 (1960).

[23] N. P. Samios, Phys. Rev. Letters **4**, 470 (1960).

The observed distribution in x, expressed as x/E, where E is maximum energy available to the pair (138.1 Mev for the γ reaction, 135.1 Mev for the π^0 reaction), is shown in Fig. 6.

The strong peaking at small values of x/E indicates that the photons involved are nearly real so the calculated conversion probabilities are very weakly structure dependent and should be quite reliable. The dotted curve is for the π^0 and the full curves for the γ reaction. The lower full curve represents the contribution from transverse photons and, since the magnetic moment and size effects almost cancel, the area between the two full curves is essentially the contribution from longitudinal photons. It is clear that the experimental points are not sufficiently accurate to detect the small effects. The points at small x/E correspond to small opening-angle pairs for which the fractional error in the opening angle is large.

The distribution in opening angle θ should go as $1/\theta$ for $\theta > 1.7°$.[11] The results are shown in Fig. 7, for

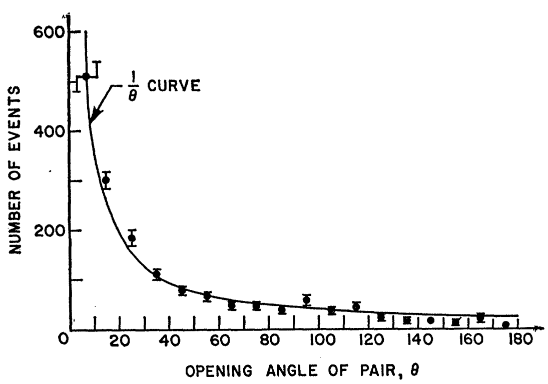

FIG. 7. Opening-angle distribution of events. Both π^0 and γ pairs are included.

all events grouped together. The π^0 and γ pairs follow the same curve within the errors. The experimental points fall slightly below the curve for large θ.[24]

[24] D. W. Joseph (private communication) has pointed out that for the π^0 decay the $1/\theta$ law holds only for the angular region $5° \lesssim \theta \lesssim 100°$ and that for $\theta \to 180°$, $d\rho/d\theta$ vanishes linearly with θ. This is a result of the fashion in which phase space vanishes. Such a curve is in good agreement with the data presented in Fig. 7.

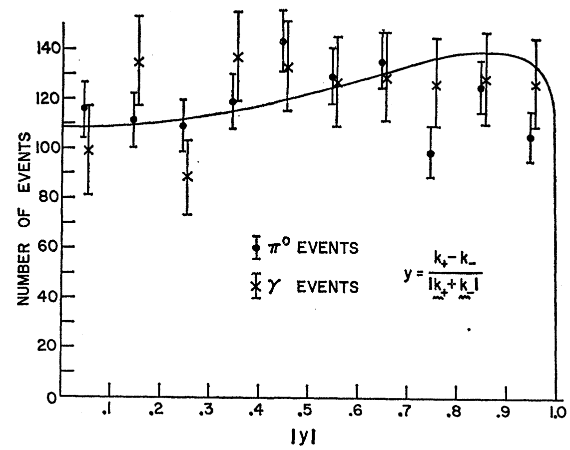

FIG. 8. Distribution of pairs in momentum partition. The curve is folded over and plotted as a function of $|y|$. The theoretical curve from Kroll and Wada (reference 12) is the same for both π^0 and γ pairs.

The other parameter of the theory is the momentum partition, y, defined as

$$y = (k_+ - k_-)/|\mathbf{k}_+ + \mathbf{k}_-|.$$

The results are shown in Fig. 8, where the γ events have been normalized to the same total number of events as the π^0's. The theoretical curve is essentially the same for both π^0 and y events. For both kinds of event there seem to be slightly fewer cases of high y, corresponding to very asymmetric energy sharing, than would be predicted by the theory. This is possibly correlated with the lack of wide-angle pairs shown in Fig. 7. A 3% systematic error has been included in P to account for this. The Panofsky ratio has also been calculated taking only events with $y < 0.7$. The result is 1.53 ± 0.12, which agrees with the measurement using all the events.

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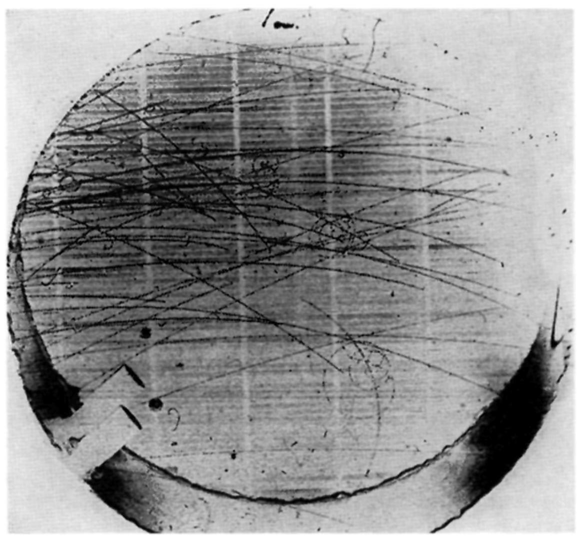

Fig. 1. One view of the stopping pion beam, showing an electron pair.