Decay of Neutral Pions*

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The proper mean life of the neutral pion is measured by a new method which utilizes a large relativistic time dilation. Negative pions of 3.5 Bev were permitted to make interactions in K-5 nuclear emulsion. High-energy neutral pions from some 2000 interaction stars were observed when they decayed by the Dalitz mode. The distances from the star centers at which they decayed were accurately measurable. The momentum spectrum of the neutral pions was assumed to be the same as that of the charged pions produced in the same interactions. Angular distributions of the secondary charged and neutral pions are presented separately. The mean transverse momentum of the charged pions was measured and found to be 250 ± 10 Mev/c. The neutral pion mean life is $(1.9_{-0.8}^{+1.3})\times10^{-16}$ sec.

WE have completed the first phase of a study of neutral pions produced by negative pions in nuclear-research emulsion. This part of the work was chiefly directed toward a measurement of the mean life of the neutral pion. Incidental information of some importance on the production process was also obtained.

A number of workers have attempted to measure the mean life of the neutral pion by direct observation of its flight path in emulsion, using the Dalitz decay mode ($\pi^0\rightarrow e^++e^-+\gamma$). Recently two reports of work that probably constitutes measurement of the mean life were published,[1,2] but the observed flight paths of the mesons (about one-fourth the wavelength of the light used for the observation) are at the limit of measurability. A significant feature of our new experiment is the production of "large" gaps corresponding to the pion paths.

When we designed the experiment, there was no information that permitted us to assume that the mean life is as large as has been found. We were obliged to plan an experiment capable of measuring a quantity an order of magnitude smaller. This required the development of a rather elaborate measurement and data-reduction equipment. We also introduced a principle that lowers almost indefinitely the theoretical minimum observable mean life. The proper time, τ, in the rest frame of the pion varies with the flight path, s, according to the formula $\tau=s(1-\beta^2)^{\frac{1}{2}}/\beta c$. The factor $(1-\beta^2)^{\frac{1}{2}}$ produces a relativistic flight-path dilation which can be made 10 or 100 by observing neutral pions of the appropriate velocities.

In our experiment (see Fig. 1), the point of decay, P, of the π^0 is taken to be the vertex of the (e^+,e^-) pair. The origin, O, of the meson is found from the intersection of the trajectories of near-minimum-ionizing particles produced at the π^- interaction point. Experiments with Ilford K-5 emulsion and L-4 emulsion hypersensitized with triethanolamine were made, but our measurements were carried out with normal K-5 emulsions. The higher grain density obtained with hypersensitization in this experiment turned out to be not as important as the freedom from a background of single grains.

We made exposures to two negative pion beams. The first, of 3.5-Bev energy, was made in Berkeley. In the second, which was made in collaboration with W. O. Lock of CERN, the pion energy was 16 Bev. The present data are derived from the first exposure. If we find later that the higher energy gives an advantage, the results of the second experiment also will be reported. Because some of the pair angles become smaller, the star center more poorly defined, and the multiple scattering of the secondary charged particles more difficult, the higher incident energy is not necessarily better for this experiment. Nevertheless, there are obvious advantages in increasing the energy and thus producing pions having higher energies. We expect (a) larger gaps due to relativistic dilation, (b) smaller error in fitting least-squares straight lines through the grains of the tracks, and (c) the pions to be contained in a smaller forward cone.

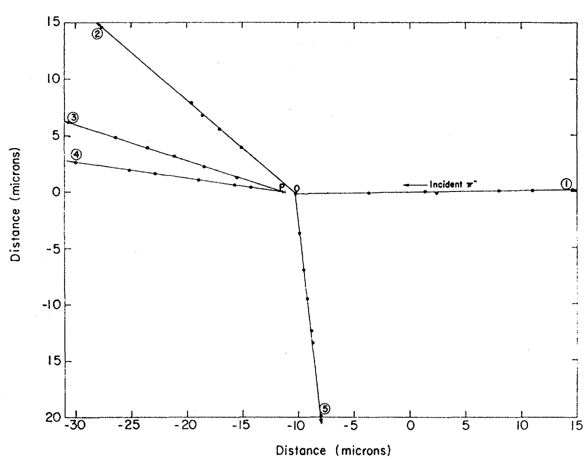

FIG. 1. An event in which a π^0, produced at point O, decays in the Dalitz mode, $\pi^0\rightarrow e^++e^-+\gamma$, at point P (event $V6$–228). Points are centers of grains; straight lines are least-squares fits. Tracks 2 and 5 are near-minimum tracks; tracks 3 and 4 are the (e^+,e^-) pair.

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† State scholar from the Union of Burma.
[1] R. F. Blackie, A. Engler, and J. F. Mulvey, Phys. Rev. Letters **5**, 384 (1960).
[2] R. G. Glasser, N. Seeman, and B. Stiller, Phys. Rev. **123**, 1014 (1961).

Production of neutral pions by pions rather than protons was tried in the hope that a portion of the events would be of an elastic or quasi-elastic charge-exchange type. Whereas in the K-meson decay production of neutral pions the pion momentum is low but accurately known in direction and magnitude, our method of production requires the separate determination of the path vector and momentum of the pion. Although the momentum was measured for a number of individual neutral pion events, we chose a statistical approach. In this way we could use most of our gap data. For the present we have assumed that the π^0 momentum spectrum is the same as that which we measured for the charged pions produced in the same angular interval. We realize that a certain, probably not important, error is thereby introduced. As knowledge of the π^0 spectrum improves, however, our result will be bettered.

All stars having two "minimum"-ionizing secondaries plus one or more near-minimum secondaries were analyzed. The primary and at least one secondary were needed to define the point O (Fig. 1). For the measurements we used a Koristka MS2 microscope with the stage modified in such a way that it could be rotated from one position stop to another at 90 deg. The filar micrometer eyepiece read-out shaft was coupled to an analog-to-digital converter. This "digitizer" fed through an electronic translator assembly into an IBM card-punch machine. We determined the relative x and y coordinates of the centers of the six grains closest to the star center for each fast track, including that of the primary π^-. An IBM-650 computer was programmed to calculate the least-squares best straight-line fit to each track. It also calculated the intersections of pairs of lines and their errors.

When the star center was found from the intersections of more than two pairs of tracks, the average distance between these points was $0.06\pm0.01\ \mu$. Typically, then, the location of the star center (point O in Fig. 1) was known to better than $0.03\ \mu$. An e^+, e^- pair was suspected when a pair of minimum-ionizing tracks did not intersect in the small region where all the others did (including nonminimum tracks and the primary). Each event was measured by at least two different trained observers, often on different days. The agreement was compatible with quoted statistical errors. The tracks of the suspected electrons were then followed until they left the plate. In most cases when one or both of the tracks stayed in the emulsion for 5 mm or more, one could show that they were electrons. In no case was a suspected electron found not to be one.

The momentum spectrum was found by measuring the multiple scattering of secondary tracks having dip angles of less than 6° and correcting the spectrum for the bias thus introduced. Limiting the dip angle to 6° was necessary to avoid the effect of "spurious scattering," which increases with dip angle. The measured momentum spectrum derived from charged secondary pions emitted at laboratory production angles of $\leqslant 60°$ is shown in Fig. 2(a). The transverse-momentum distribution for secondary charged pions at all angles, corrected for bias in dip angles, is shown in Fig. 2(b). For more reliable multiple-scattering measurements, the 600-μ emulsion was exposed in the form of glass-backed plates.

The probability $P(s)$ that the neutral-pion path exceeds a distance s before decay is given by

$$P(s)=\int_0^\infty [\exp(-s/c\eta\tau)]f(\eta)d\eta, \qquad (1)$$

where τ is the neutral pion's proper mean life in seconds, η is the pion momentum in Mev/c divided by its rest energy in Mev, and c is the velocity of light. The normalized momentum spectrum $f(\eta)d\eta$ was found as described above.

By careful scanning, 2000 π^- stars in emulsion yielded 61 associated electron pairs. Only the projection of the path of the neutral pion on the plane of the emulsion could be determined with good accuracy. For the

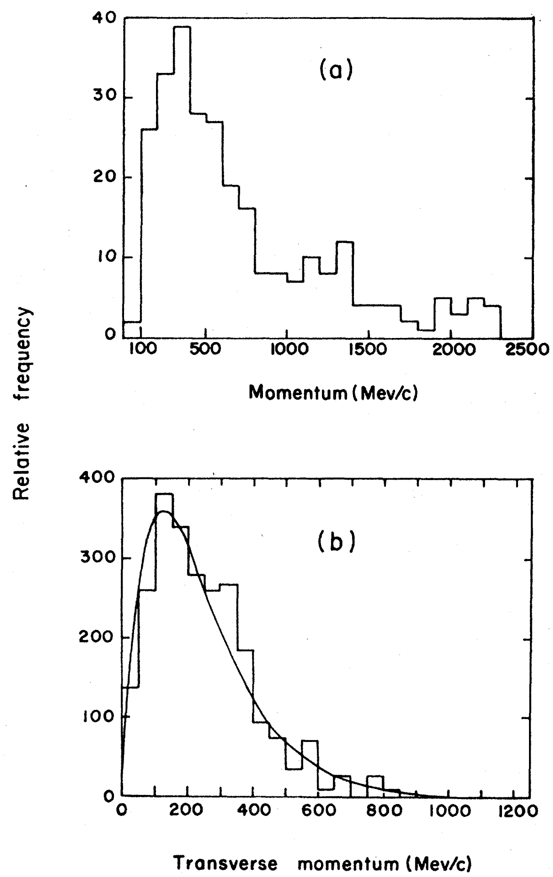

FIG. 2. (a) Measured momentum spectrum of secondary charged pions. (b) Distribution of transverse momentum p_T for all measured secondary charged pions. The smooth curve is the best χ^2 fit obtained by using $f(p_T)=Kp_T\exp(-p_T/125)$; $\langle p_T\rangle=250\pm10$ Mev/c.

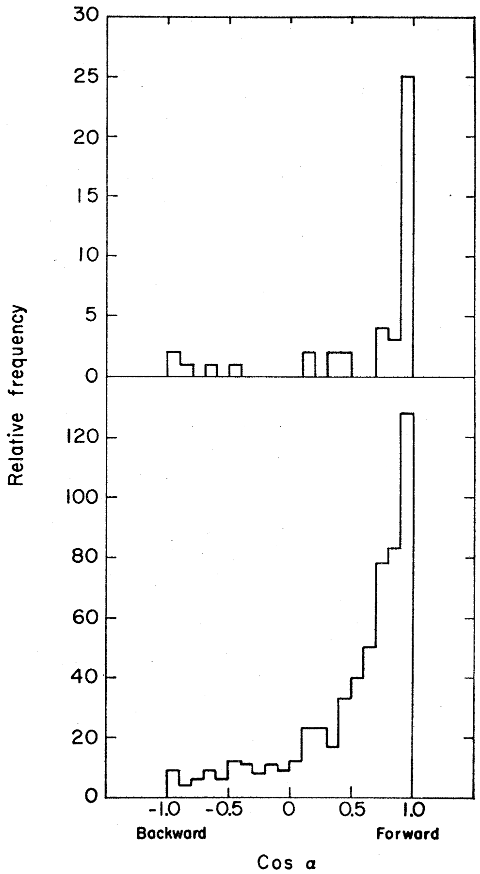

FIG. 3. (a) Angular distribution of neutral pions; α is the projected angle relative to incident-pion direction. (b) Angular distribution of secondary charged pions; α is the space angle relative to incident-pion direction.

mean-life measurement, we selected trajectories making projected angles of $\leqslant 60$ deg with the path of the primary pion. Figure 3(a) shows that the angular distribution is very peaked forward, and that actually no events were found with projected angles between 40 and 60°. Although it is possible that a π^0 meson outside of a 60-deg cone could be included by our method of selection, the error involved seems negligible, partly because a bias exists against observing an event with a dip angle near 90°, and partly because a large dip angle would have been measurable in the longer of the flight paths. The space-angle distribution of the charged secondary pions is shown in Fig. 3(b).

The projected path length of the π^0 meson in no case exceeded 2.31 μ. The average gamma-ray conversion length being over 4 cm, probably none of the pairs we have observed in this interval are from ordinary π^0 gamma-ray conversion. Table I gives projected path lengths of all measurable neutral pions and angles of emission relative to the primary negative pion. The opening angles of the electron pairs in the laboratory system are also listed. At high pion energies, some angles are increased and others decreased. The deficiency of very small angles is explained below. For a gap observation to be considered a measurement, the gap length had to exceed considerably the error in its measurement.

Among the events missed or unmeasured were the following types: (a) Events with only two secondary minimum-ionizing tracks. Another secondary is needed to define the star center; therefore no measurement could be made. (b) Events with a very close (e^+,e^-) pair. When the angle between the tracks was less than 3°, the measurement error often became too large to establish the existence of a gap. (c) Events with very small gaps which lie within the "circle of confusion" around the star center.

The projected path-length distribution for neutral pions emitted in the 60° interval is shown in Fig. 4(a) as points. The solid curve is the distribution calculated from Eq. (1) with $\tau = 1.8\times10^{-16}$ sec and the assumed

TABLE I. Measured π^0 projected path.

Event No.	Projected π^0 path length (microns)	Projected angle of π^0 path relative to incident π^- (deg)	Opening angle of pair, lab (deg)
V3–3	0.80±0.31	18.5	4.3
V6–86	1.03±0.14	142.3	7.3
V6–184	0.68±0.14	18.5	8.9
V6–298	0.59±0.11	16.5	8.3
V6–228	0.98±0.08	9.3	9.6
V6–352	2.31±0.34	20.9	2.9
V6–47	0.42±0.09	7.3	19.8
V3–83	1.25±0.19	35.1	4.7
V3–72	0.51±0.09	38.1	13.1
V6–391	0.73±0.02	4.3	72.2
V6–140	0.95±0.05	152.6	15.0
V3–41	1.05±0.17	14.1	6.0
V6–410	0.35±0.04	11.1	39.9
V6–189	0.55±0.04	9.4	16.9
V6–235	0.25±0.03	27.3	37.0
V6–75	1.53±0.06	78.7	17.6
V2–124	1.44±0.25	5.2	4.7
V2–84	1.06±0.16	159.6	6.9
V2–114	1.30±0.15	84.0	10.2
V6–62	1.18±0.04	3.8	42.6
V6–50	0.93±0.04	24.1	34.4
V6–94	0.49±0.11	19.2	13.2
V6–37	0.27±0.03	38.0	31.8
V2–97	0.25±0.02	169.6	41.5
V6–111	0.30±0.02	60.4	49.8
V2–110	0.98±0.10	2.4	15.3
V2–113	0.51±0.06	12.8	18.3
V2–209	0.20±0.05	68.2	24.9
V2–244	0.37±0.05	61.9	12.9
V4–140	0.19±0.02	16.2	30.8
V4–149	0.72±0.06	13.3	14.5
V4–137	0.39±0.03	39.8	34.0
V4–209	0.25±0.07	10.7	20.5
V4–207	0.49±0.05	18.8	21.7
V2–66	0.34±0.06	3.3	17.8
V6–211	0.53±0.08	3.7	22.3
V4–322	1.37±0.27	25.1	4.4
V4–436	0.24±0.05	30.5	21.3
V4–479	0.90±0.05	70.3	19.4
V6–433	0.35±0.02	40.0	55.8
V6–488	0.88±0.04	17.8	27.0
V6–137	0.71±0.05	8.1	18.5
V6–572	1.99±0.03	114.9	6.0

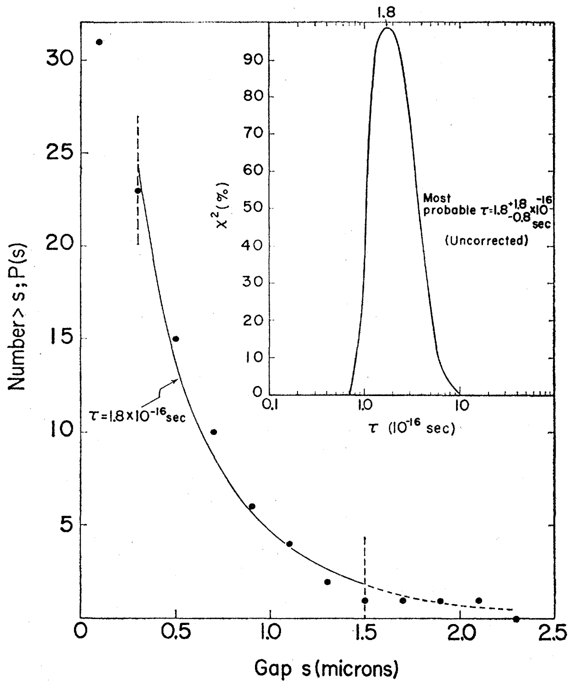

FIG. 4. (a) Integral distribution of projected gaps (π^0 path). Dotted points are experimental, and the solid curve is plotted from Eq. (1) by using the most probable τ and the measured momentum spectrum (see text). (Inset) χ^2 distribution for different values of τ. The most probable value of τ is $(1.8_{-0.8}^{+1.8})\times 10^{-16}$ sec.

momentum spectrum. There is a bias against finding gaps shorter than 0.2 μ. This restricted the region for curve fitting to the interval $s>0.2\ \mu$. Figure 4(b) shows the χ^2 distribution in percent for different assumed values of τ. From this distribution we obtained an uncorrected mean life of $\tau=(1.8_{-0.8}^{+1.8})\times 10^{-16}$ sec. If the primary track is considered to be the x axis, then the z component—perpendicular to the emulsion surface—of the π^0 path was not observed directly. Its root-mean-square value was estimated from the mean-square value of the y component, and τ was corrected to $\tau=(1.9_{-0.8}^{+1.8})\times 10^{-16}$ sec.

The confidence interval found in this way can be somewhat reduced because the total number of pairs has not yet been used.

The experimental branching ratio into the Dalitz decay mode is 0.01166 ± 0.00047, according to the measurement of Samios.[3] We assume approximately half as many secondary neutral pions as charged, but like the assumption regarding the momentum spectrum, this proportion may be improved in the future. Applying the Samios ratio, one would expect 43 neutral pions decaying in the Dalitz mode in the 60° cone. This number of pions is obtained from the total number of secondary charged pions with a mean multiplicity of 4.6. We measured 32 events in the 60° cone. An additional 12 electron pairs of types (a) and (b) were observed, making a total observed number of 44. Unfortunately there seems to be no reliable means for estimating the number of events of type (c) that were completely missed. Therefore, we can only put a lower limit of 44 on the number. Using this as an additional datum leads to a calculated mean life of 3.2×10^{-16} sec —effectively an upper limit. Therefore our preliminary mean-life measurement is

$$\tau=(1.9_{-0.8}^{+1.3})\times 10^{-16}\ \text{sec}.$$

This is in good agreement with recent measurements by Blackie *et al.*$(3.2\pm 1.0\times 10^{-16})$,[1] Glasser *et al.*$(1.9\pm 0.5\times 10^{-16})$[2], and Tollestrup *et al.*$(\geq 5\times 10^{-17})$.[4]

ACKNOWLEDGMENTS

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[3] N. P. Samios, Columbia University Physics Department Report Nevis-91, 1961 (unpublished). See also M. Derrick, J. G. Fetkovitch, T. H. Fields, and J. Deahl, *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York, 1960), p. 32; R. H. Dalitz, Proc. Phys. Soc. (London) **A64**, 667 (1951); D. W. Joseph, Nuovo cimento **16**, 997 (1960).

[4] A. V. Tollestrup, S. Berman, R. Gomez, and H. Ruderman, *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York, 1960), p. 27.