PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

# Lifetime of the Neutral Pion*

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(Received January 7, 1957)

A new upper limit on the $\pi^0$ lifetime has been obtained by using 12 $K_{\pi 2}^+$ endings in nuclear emulsion where the $\pi^0$ decays by a direct pair, $\pi^0 \rightarrow (e^+ + e^-) + \gamma$. The distance traveled by the $\pi^0$ before decay was measured from the intersection of the $K^+$ and $\pi^+$ tracks to the intersection of the pair and $\pi^0$ (colinear with $\pi^+$). The inherent accuracy of the measuring technique was found to be ~0.5 micron per event by using $\tau^+$ secondaries as mock events. With the statistics of 12 events it should be possible to detect a $\pi^0$ decay length of ~0.2 micron or greater. Our data give no indication of a displacement of pair origins from the $K$ endings. Thus the $\pi^0$ decay length is probably less than ~0.2 microns. This corresponds to a lifetime of less than $5 \times 10^{-16}$ sec. Information on the upper limit of the $\pi^0$ lifetime is obtained from a plot of the likelihood function *vs* $\pi^0$ lifetime. The likelihood function is down by a factor of 30 for a lifetime of $1 \times 10^{-15}$ sec and is rapidly decreasing for longer lifetimes.

## INTRODUCTION

ONE of the by-products of our experiment to measure heavy meson lifetimes[1] is a measurement of the lifetime of a light meson, the neutral pion. In the decay of the $K_{\pi 2}^+$, a neutral pion is emitted with a velocity $\beta = 0.835$ in the direction opposite to the observed $\pi^+$ track. About 1.2% of these neutral pions should decay according to the alternate mode, $\pi^0 \rightarrow (e^+ + e^-) + \gamma$.[2] We have observed six such events during the course of examining about 3500 $K^+$ endings. In addition to our six $K_{\pi 2}$'s with direct pairs, we have measured six others which were found by other emulsion groups.

If the neutral pion had a lifetime of $1 \times 10^{-15}$ sec, the mean decay length from the $K^+ - \pi^+$ intersection to the $\pi^+$-pair intersection should be 0.455 micron. The experimental determination of this distance gives a straightforward determination of the $\pi^0$ lifetime which is free from the various assumptions upon which previous estimates depend.[3–5] The decay distance per event was measured with an accuracy ~0.5 micron as determined by measurements of $\tau^+$ secondaries of comparable grain density. Within the accuracy of the technique used, our data give no indication of a displacement of pair origins from the $K$ endings. The twelve decay distances and their individual errors are listed in Table I. The full information which can be obtained from this data concerning the $\pi^0$ lifetime is shown in Fig. 1. It is seen that the probability of getting our results when one assumes a lifetime $10^{-15}$ sec or greater is much smaller than the probability when one assumes a lifetime $\sim 10^{-16}$ sec.

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission, and by a National Science Foundation research grant.
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## MEASUREMENT TECHNIQUE

The measurement involves establishing three intersecting lines: the $K^+$ direction, the $\pi^+$ direction, and the pair direction. This is done by drawing the event grain by grain using a camera lucida. The magnification at the drawing board was 6000 to 1. Figure 2 shows one of the twelve drawings. In this case the pair appears to originate at a distance of 0.42 micron along the $\pi^+$ rather than the $\pi^0$. In Fig. 2 this is the distance between the two arrow heads. After correcting for the $\pi^+$ dip angle this decay distance becomes $-0.64$ micron.

One might expect the inherent accuracy of this procedure to be about one grain diameter or ~0.5 micron. The inherent standard deviation in this procedure was

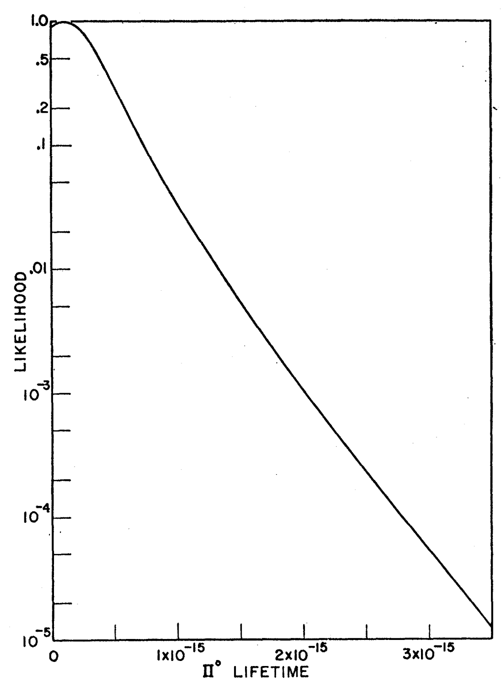


FIG. 1. The ordinate is the likelihood function or the relative probability that our twelve measurements turn out the way they did if one assumes different values for the $\pi^0$ lifetime.

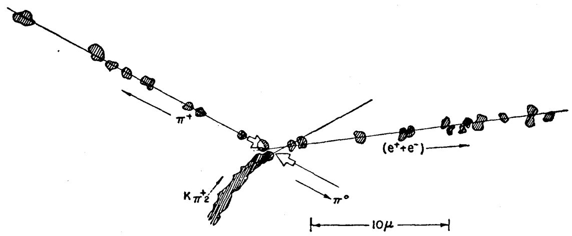


FIG. 2. Camera lucida drawing of event No. 10. The measured decay distance is the distance between the arrow heads. In this case the measured decay distance is negative since the pair line happens to intersect the $\pi^0$ line on the wrong side of the $K$ ending.

determined empirically by measuring 32 intersections of tau endings with two of the pion secondaries. Pion secondaries ~30 Mev were used. In this case the true decay distance must always be zero. Figure 3 shows one of the tau meson drawings where the angle between the two secondaries which were used is 8.0°. One would expect the accuracy of determining the intersection of two tracks to go as $\csc\theta$. We assumed the error of an individual event would be of the form

$$\sigma = [a^2 + b^2(\csc^2\theta_1 + \csc^2\theta_2)]^{\frac{1}{2}}, \tag{1}$$

where $\theta_1$ is the angle between the $K^+$ and $\pi^+$, and $\theta_2$ is the angle between the $\pi^+$ direction and the angle bisector of the pair. The 32 tau "decay distances" gave the values: $a = 0.332$ micron, and $b = 0.103$ micron. Equation (1) was used in determining the error of each of the 12 events. This error is then multiplied by $\sec\alpha$, where $\alpha$ is the original dip angle of the $\pi^+$. Table I lists each of the 12 decay distances and their individual errors. A check can be made on this error procedure by examining the internal consistency of the 12 decay distances. In this check, the error of each measurement is assumed to be proportional to, but not equal to, the value given by Eq. (1). Then the rms error of the mean is calculated assuming these are 12 repeated measurements of the same quantity. This internal rms error of the mean is 0.11 micron which is quite consisitent with the value 0.16 micron which is obtained when the errors in Table I are used directly.

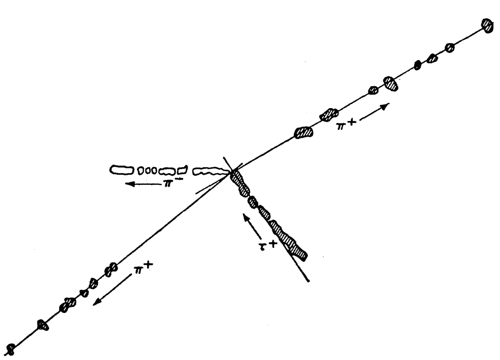


FIG. 3. One of the $\tau^+$ endings used in the determination of the accuracy of the measuring technique. Only the light secondary tracks (in this case the two $\pi^+$'s) were used to simulate a $K_{\pi 2}$ with direct pair.

Individual variations were found to exist in the criteria used to draw the best-fit track directions and occasionally in the interpretation of grains near the $K_{\pi 2}$ ending. Comparison of drawings of the same event by different observers showed variations which were usually well within the error given by Eq. (1). Repeated drawings by the same observer showed remarkable reproducibility. In order that our results not be subject to individual variation, all the $K_{\pi 2}$ and $\tau$ data used in this paper were obtained from the drawings of the same person.

## RESULTS

If the $\pi^0$ always decayed at a fixed distance from the $K$ ending, the correct statistical procedure would be to determine the weighted mean of the 12 decay distances with $1/\sigma^2$ as the weighting factor. Our data give a value 0.02 micron for this weighted mean. The rms error of this mean is 0.16 micron when one uses Eq. (1)

TABLE I. List of the twelve $K_{\pi 2}$ events with direct pairs. The measured value of each decay distance is $x$. The rms error of each measurement is $\sigma$. The angle $\alpha$ is the original dip angle of the $\pi^+$. $\theta_1$ is the angle between the $K$ and the $\pi^+$, and $\theta_2$ is the angle between the $\pi^+$ and the pair.

| Event | $x$ (microns) | $\sigma$ (microns) | $\alpha$ | $\theta_1$ | $\theta_2$ |
|---|---|---|---|---|---|
| 1 | 0.20 | 0.68 | ~0° | 40° | 10° |
| 2 | 0.33 | 0.44 | ~0° | 24° | 59° |
| 3 | 0.17 | 0.46 | 28° | 59° | 38° |
| 4[a] | 0 | 0.7 | 20° | 6.5° | 81° |
| 5[b] | 0.78 | 0.82 | 43° | 63° | 12° |
| 6 | 0 | 0.76 | 61° | 66° | 83° |
| 7 | 0 | 0.42 | 27° | 79° | 80° |
| 8[c] | −0.75 | 0.53 | ~0° | 46° | 15° |
| 9[a] | −0.21 | 0.49 | 40° | 80° | 84° |
| 10[c] | −0.64 | 0.61 | 49° | 58° | 37° |
| 11[c] | 0.34 | 0.45 | 24° | 39° | 40° |
| 12 | 1.28 | 2.90 | 82° | 75° | 62° |

[a] Berkeley events.
[b] Massachusetts Institute of Technology event.
[c] Rochester events.

for the errors of the individual measurements. However, since the distance at which the pair appears is distributed according to an exponential decay, the procedure of the weighted mean is statistically efficient only in the limit where the decay length is much smaller than the errors of each measurement. In general, the correct statistical procedure is to calculate the relative probability that our 12 decay distances and their 12 errors turn out the way they did as a function of the lifetime. This relative probability is known as the likelihood function and is plotted in Fig. 1. Let $x$ be the measured decay distance of a single event; then, if $l$ is the true decay distance, $x$ will be distributed according to

$$p(x,\sigma;l) = (2\pi\sigma^2)^{-\frac{1}{2}} \exp\left\{-\frac{(x-l)^2}{2\sigma^2}\right\},$$

where $\sigma$ is the error of the individual measurement. We know that $l$ is distributed according to

$$q(l) = (1/L)e^{-l/L},$$

where $L=\gamma\beta c\tau$ is the true decay length and $\tau$ is the $\pi^0$ lifetime. Thus

$$P(x,\sigma;\tau)=\int_0^\infty p(x,\sigma;l)q(l)dl,$$

when considered as a function of $\tau$, is the likelihood function for a single event. The likelihood function for a collection of 12 events is

$$Q(\tau)=\prod_{i=1}^{12} P(x_i,\sigma_i;\tau).$$

The quantity $L(\tau)=Q/Q_{\max}$ is plotted in Fig. 1. Note that a $\pi^0$ lifetime of $1\times10^{-15}$ sec is down by a factor of 30.

## DISCUSSION

As seen from Fig. 1, the $\pi^0$ lifetime is most likely less than $1\times10^{-15}$ sec. The value which corresponds to a 10% relative probability is $7\times10^{-16}$ sec. Our result is consistent with the evaluation of the lowest order term in perturbation theory for pseudoscalar coupling in a pseudoscalar field, which gives a lifetime of $7\times10^{-17}$ sec for $g^2/4\pi\hbar c=10$.[6]

Our result is in good agreement with the experimental limits $0<\tau<4.8\times10^{-15}$ sec obtained by Schein *et al.*[4] However, we are in poor agreement with the value $2.5<\tau<14\times10^{-15}$ sec obtained by Anand[3] and the value $0.7<\tau<5\times10^{-15}$ sec obtained by Brisbout *et al.*[5] In both of these papers the limits are set to include a 90% confidence interval.

Perkins[7] has pointed out that the value of Anand[3] should be revised downward because of the effect of the reduction in ionizing power of a pair when the electron and positron spacing is less than the maximum impact parameter for ionization loss. This effect has recently been observed in high-energy pairs.[7,8]

One possible systematic effect in the work of Brisbout *et al.* that would contribute to an overestimate of the lifetime is that of the nonzero angle between the pair direction and the initial gamma due to nuclear recoil.[9,10] This effect may possibly be enhanced when one selects pairs with small opening angle. Brisbout *et al.* base their $\pi^0$ lifetime limits on three pairs which were selected from a large number of high-energy pairs occuring in high-energy cosmic-ray jets.

Some of the advantages of using direct pairs from $K_{\pi2}$'s are: the $\pi^0$ direction is known, the $\pi^0$ energy is known, the pair is known to originate from a $\pi^0$, the $\pi^0$ is known to originate from the $K$ ending, there is no selection bias which can influence the lifetime result (at least for lifetimes this short), the accuracy of the measuring technique is known, and the result is independent of variation of ionizing power of the pairs. In our experiment we estimate that at least 80% of the events used are $K_{\pi2}$'s with direct pairs. The main source of false events would be direct pair decay of $\pi^0$'s in $K_{e3}\rightarrow e^++\nu+\pi^0$ and $K_{\mu3}\rightarrow\mu^++\nu+\pi^0$. If all $K_{e3}$ and $K_{\mu3}$ mesons decay by the $\pi^0$ mode, then the frequency of this type event is determined by the relative abundances of $K_{e3}$ and $K_{\mu3}$ as compared to the $K_{\pi2}$. According to the most recent relative abundances[11] this would contribute a background of less than 20%. Actually the background would be less because a significant number of such events would have low-energy electrons or muons, or the pair would clearly be of the wrong energy. Other background sources would be the possibility of the direct decay modes $K^+\rightarrow\pi^++\gamma+\text{pair}$, $K^+\rightarrow\mu^++\nu+\text{pair}$, and $K^+\rightarrow e^++\nu+\text{pair}$. Upper limits can be put on these direct modes by comparing them with the respective modes: $K^+\rightarrow\pi^++\text{pair}$, $K^+\rightarrow\mu^++\nu+\gamma$, and $K^+\rightarrow e^++\nu+\gamma$.[12] Of these three modes, the first has never been seen, and the other two would be included in the $K_{\mu3}$ and $K_{e3}$.

Direct pair decay of $\pi^0$'s from $\tau'\rightarrow\pi^++2\pi^0$ does not contribute because the $\pi^+$ track is noticably above minimum ionization. We have found three such events out of the 3500 $K$ endings examined at Columbia. In each of these events the heavy secondary stopped in the stack and $\pi$-$\mu$-$e$ decayed.

All twelve of the events used in determining the $\pi^0$ lifetime appeared consistent with a $K_{\pi2}$ with direct pair. In two of these events one member of the pair was assumed to be of low energy since only one definite high-energy electron could be found. No correction was made for the possibility that one or two of the twelve events might have been non-$K_{\pi2}$ events. The effect of a 20% contamination of non-$K_{\pi2}$ events would be to reduce our $\pi^0$ lifetime result by no more than 20% from its true value.

We are indebted to the nuclear emulsion groups at the University of Rochester, the Radiation Laboratory of the University of California, and the Massachusetts Institute of Technology for contributing half of the events used. We are particularly grateful to Dr. T. F. Hoang who supplied three events from Rochester, Dr. R. W. Birge who supplied two events from Berkeley, and Dr. R. A. Schluter who supplied one event from the Massachusetts Institute of Technology. In addition we wish to thank Mr. P. Baumel, Mrs. E. Bierman, Mrs. J. Impeduglia, Mrs. M. Johnson, Miss J. Lee, and Mr. E. Levin of the Columbia Nuclear Emulsion Group for locating and analyzing the data.

*Note added in proof.*—Two more events have been found at Columbia which shorten our $\pi^0$ lifetime result. Event 13 has $x=-0.77$ micron and $\sigma=1.77$ micron. Event 14 has $x=-0.80$ micron and $\sigma=1.28$ micron.

A private communication from D. H. Perkins informs us that more recent cosmic-ray jet data indicate a lifetime shorter than that reported in reference 5.

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