Mean Life of the Positive π-Meson*

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Photoproduced π^+ mesons stopped and decayed in a xylene-terphenyl liquid scintillation counter. The pulses from the counter were amplified and displayed on two oscilloscopes. The entire sequence $\pi^+\rightarrow\mu^+\rightarrow e^+$ could be observed, and from the measurement of 670 π-μ decay times, a value of $(2.53\pm0.10)\times10^{-8}$ sec was obtained for the π^+ mean life.

I. INTRODUCTION

IN a previous communication[1] the writer, Thomas, and Henri have described some preliminary results of an experiment designed to measure the mean life, τ_{π^+}, of π^+ mesons. Photoproduced π^+ mesons were allowed to decay in a stilbene crystal, and on the basis of 57 observed decays a value for τ_{π^+} of $(1.65\pm0.33)\times10^{-8}$ sec was obtained. Subsequently, Chamberlain, Mozley, Steinberger, and Weigand[2] and Weigand[3] using similar techniques found a value of $(2.58\pm0.14)\times10^{-8}$ sec, and Jakobson, Schulz, and Steinberger[4] using an electronic counting method found $(2.54\pm0.11)\times10^{-8}$ sec. An improved version of our preliminary experiment has now been completed and a value of $(2.53\pm0.10)\times10^{-8}$ sec has been found.

The most recent determination of the π^- mean life,[5] $(2.92\pm0.32)\times10^{-8}$ sec, was based upon observations of the decay of π^- mesons in flight. This value is seen to be in reasonable agreement with the later π^+ mean life determinations.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement used in the present measurement is shown in Fig. 1. γ-rays from the MIT synchrotron struck the polyethylene target, producing π^+ mesons. Some of these mesons traversed the two absorbers, S_1 and S_2, passed through counter A and stopped in counter B. Counters A, B, and C consisted of aluminum cans cemented to photomultiplier tubes and filled with a terphenyl-xylene solution. The pulses originating in counter B were amplified, delayed, and displayed on two oscilloscopes, one having sufficient over-all resolution to show the π-μ decay when the decay time was not too short, and the other arranged to show the μ-e decay. Hence the complete decay, $\pi\rightarrow\mu\rightarrow e$, could be observed when the decay times were favorable. The sweep circuits associated with the two oscilloscopes were triggered by AB–C anticoincidences. That is, the sweeps were triggered whenever simultaneous pulses were received from counters A and B unaccompanied by a pulse from counter C. The oscilloscope traces were photographed on a continuously moving film.

The apparatus was located 16 feet from the synchrotron target, and the beam at this location was 2 inches in diameter after collimation. The synchrotron was pulsed twice a second, and the γ-rays were emitted more or less uniformly over a period of about 1600 microseconds. Each burst of γ-rays produced an ionization of about 0.4r in a Victoreen r meter placed 1 meter from the synchrotron target and surrounded by $\frac{1}{8}$ in. of lead. The polyethylene target was 2 g cm^{-2} thick and essentially covered the beam in its transverse dimensions.

The experimental data were obtained in about 40 hours of synchrotron running time. During this time, there were approximately 12,000AB–C anticoincidences, and hence about 12,000 oscilloscope sweeps. Of these events, about 1500 corresponded to the stopping of π^+ mesons in counter B.

The background rate of pulses with heights corresponding to an energy loss greater than 1 Mev in counter B, was about 2 per synchrotron pulse. The AB coincidence rate was about three times as large as the AB–C anticoincidence rate.

III. SELECTION OF EVENTS

For purposes of discussion the various pulses will be given phenomenological descriptions. The times referred

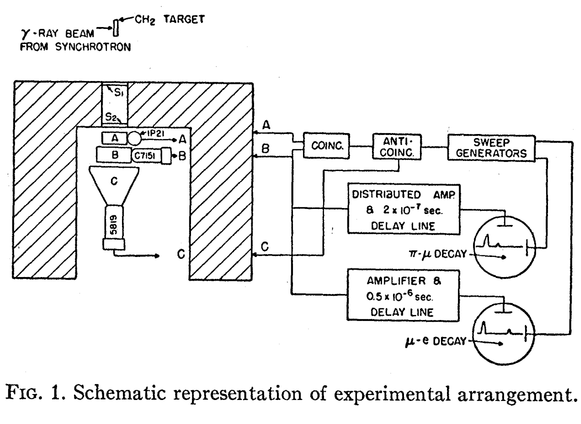

FIG. 1. Schematic representation of experimental arrangement.

* Assisted by the joint program of the ONR and AEC.
[1] Kraushaar, Thomas, and Henri, Phys. Rev. **78**, 486 (1950).
[2] Chamberlain, Mozley, Steinberger, and Wiegand, Phys. Rev. **79**, 394 (1950).
[3] C. Weigand, Phys. Rev. **83**, 1085 (1951).
[4] Jakobson, Schulz, and Steinberger, Phys. Rev. **81**, 894 (1951).
[5] Lederman, Booth, Byfield, and Kessler, Phys. Rev. **83**, 685 (1951).

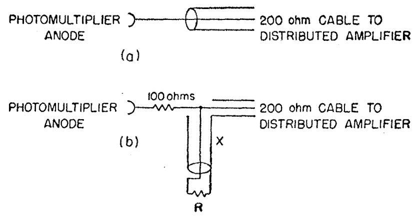

FIG. 2. Photomultiplier connections. Part *a* shows the arrangement as used in the experiment proper. Part *b* shows the arrangement for producing simulated π-μ decays. The cable *x* determined the decay time, and the resistor *R* determined the relative height of the μ-pulse. The 100-ohm resistor served to keep the photomultiplier clipping time the same for arrangements *a* and *b*.

to are measures of the interval from the start of the trace to the peak of the pulse in question.

π, the pulse responsible for the AB–C anticoincidence.
μ, a pulse following the π if $t_\mu - t_\pi < 30\times10^{-8}$ sec.
e, a pulse with a delay between 30×10^{-8} sec and 10.8×10^{-10} sec relative to the μ, or if no μ was resolved, relative to the π.

There follows a summary of the various criteria used in selecting those events suitable for inclusion in the mean life evaluation.

1. No π-μ-like event was included that was not accompanied by an electron or *e* pulse as defined above. The number of accidental *e* pulses was small, and this criterion made possible the very small number of accidental π-μ-like events.

2. It was required that the height of the *e* pulse correspond to an energy loss of at least 1 Mev.

3. π-μ-e decays having μ-e decay times less than 30×10^{-8} sec were excluded, because there was a fair probability that the electron would go through the anticoincidence counter, and so be instrumental in rejecting selectively those events with a total π-μ-e decay time as short or shorter than the anticoincidence resolving time (15×10^{-8} sec). The π^+ mean life value would have been effected by about 1 percent if this point had been neglected.

4. The discriminator on the counter *C* coincidence amplifier was set at 8 Mev, and the resolving time was about 8×10^{-8} sec. This relatively long resolving time resulted in successful triggering of the apparatus on some short π-μ decays where the π-pulse alone would have been too small. Hence for pulse heights in a limited region, there was selective triggering tending to favor short decay times. The final π-pulse-height requirement (10 Mev or greater) was therefore imposed after the heights had been measured *on the film*.

5. Some finite size of the μ-pulse was necessary to make the time measurements. As will be discussed later, the μ-pulse-height distribution was fairly narrow, and only 3 percent of the otherwise acceptable events were rejected because the μ-pulse height was too small. As discussed in Sec. IV, the smallest π-μ decay time considered for the mean life evaluation was 2×10^{-8} sec, and this time was long enough to allow the μ-pulse-height measurements to be made in all cases.

IV. FILM READING TECHNIQUE

It was felt desirable to examine the relative merits of various proposed methods of measuring the π-μ pulse separation, and to determine rationally the smallest π-μ decay time to be included in the mean life evaluation. Artificial π-μ decays with known time separation were produced, using the arrangement shown in Fig. 2. The electrical length of the cable *x* (as measured by resonating it as a half-wave line) determined the time difference of the pulses simulating π-μ decay, and the resistor *R* determined the relative height of the "μ"-pulse. A large number of these pulses were photographed and examined. Included were relative π- and μ-heights that covered the spread known to exist in the actual data, and delays from 10^{-8} to 17×10^{-8} sec. The method of measurement adopted involved measuring the distance from the start of the trace to the projection of the peak of the π- and μ-pulses on the baseline. The times corresponding to these distances were read from a graph of the sweep time *versus* distance, and the π-μ time separation was obtained by subtraction. Many measurements of the same time difference gave a distribution with a rms deviation about the average of 5×10^{-10} sec, provided this difference was at least 1.7×10^{-8} sec. Seven time differences were measured, and in no case did the average differ from the true value by more than 6×10^{-10} sec. The nature of the deviations of the averages from the true values were such, that we believe there to be no systematic error larger than 2 percent in the mean life arising from the measuring technique alone. Although the time measurements were accurate at 1.7×10^{-8} sec, they became very inaccurate at smaller times. It was felt, therefore, that 2×10^{-8} sec was a safe lower limit for the π-μ decay time measurements.

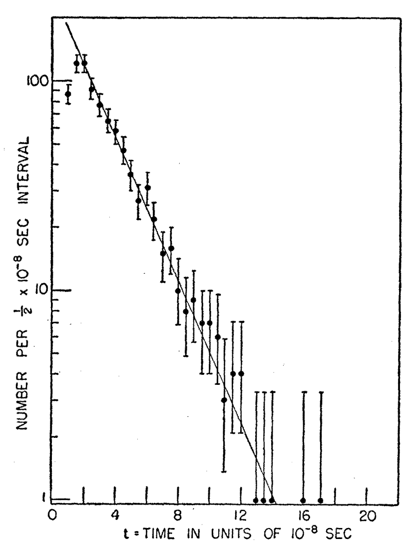

FIG. 3. Differential plot of the number of π-μ decay times per $\frac{1}{2}\times10^{-8}$ sec interval *versus* time. The slope of the line corresponds to a mean life of 2.53×10^{-8} sec. Only those decay times $>2\times10^{-8}$ sec were included in the mean life evaluation.

The sweep was recalibrated at approximately one hour intervals throughout the experiment. For this purpose, a 50.00 mc sine wave was fed directly into the amplifier and these sweeps were photographed exactly as was done for the data. The largest deviation from the original calibration was 1.5 percent. The small corrections for these deviations were applied directly to the π-μ time differences.

V. RESULTS

As mentioned before, there were about 12,000*AB-C* anticoincidences. Examination of the film revealed that 1831 of these were accompanied by an *e* pulse. About 900 of those having an *e* pulse had also a pulse interpretable as a μ, and the μ was delayed relative to the π by at least 2×10^{-8} sec in 670 cases out of the 900.

A differential plot of the number of acceptable π-μ decays per 5×10^{-9} sec interval *versus* time is shown in Fig. 3, and the corresponding integral plot of the number of decays observed after time *t versus t* is shown in Fig. 4. As has been shown by Peierls,[6] the best approximation to the mean life is just the mean of all the time observed. In the present case only decay times longer than 2×10^{-8} sec have been considered, so we have evaluated the mean life from the equation

$$\tau_m=\left(\frac{1}{N}\sum_{i=1}^{N}\tau_i-2\times10^{-8}\right)\text{ sec.}$$

This gave $\tau_m=2.54\times10^{-8}$ sec. The procedure described is valid only when there is no sensible upper limit to the time being measured. In the present case, no delay longer than 30×10^{-8} sec would have been counted. The correction for the possible neglect of these decays is entirely negligible.

There were no acceptable π-μ decays with time differences greater than 17.5×10^{-8} sec, so if any accidental events have contributed to our result, they must have occurred in the interval 2 to 17.5×10^{-8} sec. The most likely source of accidental events involved real but unresolved π-μ decays having the μ-e decay time in the interval 2 to 17.5×10^{-8} sec. An accidental but acceptable *e* pulse would then cast the event among those included in the mean life evaluation. The total number of events of this type is calculated to be 0.5. A second possible source of accidental events involved cases such as the $1831-900=931$ events in which there was an acceptable *e* pulse and no resolved μ. An accidental μ-pulse in the interval 2 to 17.5×10^{-8} sec would then cast an event such as this among those included in the mean life evaluation also. The total number of events of this type is calculated to be 0.2. The calculated number of accepted but accidental events for the entire experiment is then 0.7, and the best value for the mean life is changed to 2.53×10^{-8} sec. The lines on the differential and integral plots, Figs. 3 and 4, have been drawn with slopes corresponding to this mean life, and with a normalization such that the number of decays after 2×10^{-8} sec is 670.

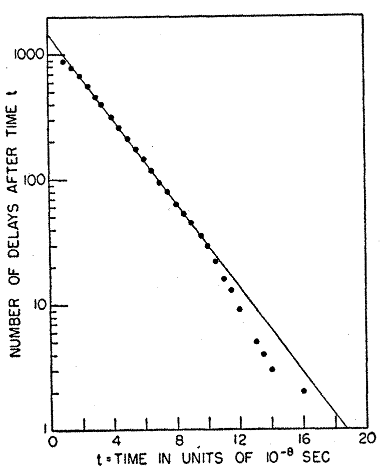

FIG. 4. Integral plot of the number of π-μ decay times larger than *t versus* time, *t*.

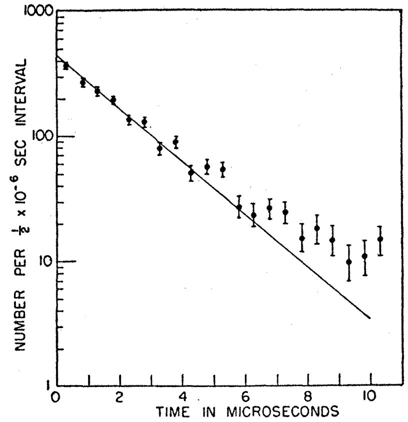

FIG. 5. Differential plot of the number of μ-e decay times per $\frac{1}{2}\times10^{-6}$ sec interval *versus* time. The slope of the line corresponds to a mean life of 2.15×10^{-6} sec.

Figure 5 shows a differential plot of the number of *e* pulses per 0.5×10^{-6} sec interval *versus* time. The line has been drawn with a slope corresponding to the known mean life of the μ-meson, 2.15×10^{-6} sec. The calculated number of accidental events included here is 7 per 0.5×10^{-6} sec interval. A background of this number of accidentals is evident from an inspection of Fig. 5.

VI. DISCUSSION OF ERRORS

The largest uncertainty in the result is due to the finite number of observations, N, and Peierls has shown that the fractional standard error is just $1/\sqrt{N}$. As discussed above, systematic errors in the measuring technique have been investigated, and have been shown to be not larger than 2 percent. This should be lowered to about 1.5 percent for consistent inclusion with the statistical uncertainty, which is given as a standard error.

[6] R. E. Peierls, Proc. Roy. Soc. (London) **149**, 467 (1935).

Godfrey, Harrison, and Keuffel[7] have reported the existence of small secondary or satellite pulses which were observed to follow the main pulse from a photomultiplier. In order to determine the effect, if any, of these satellite pulses on the π^+ mean life result, a large number of cosmic-ray pulses (see Sec. VIII) were examined. No secondary pulses were observed that could possibly have been confused with μ-pulses from the decay of π^+ mesons. The oscilloscope arrangement was such that satellites larger than 5 percent of the height of the main pulse would have been noticed. This is not inconsistent with the observations of Godfrey *et al.*, since it may be that the satellite pulse-height distribution does not depend upon the heights of the main pulses. The main pulses in the present experiment probably arose from many more photoelectrons than did the main pulses discussed by Godfrey *et al.*

It is important to note that the test measurements using artificially produced π-μ decays, as discussed in Sec. IV, reflect only on the accuracy of the film-ready technique and do not imply the existence of similar accuracy in the determination of any individual real π-μ decay time. This is because both the π- and μ-pulses in these tests were derived from the same photomultiplier current pulse. The time from the creation of the ionization and excitation in the scintillator to the appearance of the peak of the pulse is subject to fluctuations, arising for the most part, from the finite number of photoelectrons ejected from the cathode of the photomultiplier tube and from fluctuations in the photomultiplier response time. Examination of the rise times of many pulses has shown that these fluctuations are certainly much less than 10^{-8} sec. Anyway, such fluctuations as did exist were randomly distributed among all of the π-μ decays observed. It can be shown that the effect on the π^+ mean life is just to increase the standard error by a factor of $[1+(\alpha/\tau)^2]^{\frac{1}{2}}$ over what it would be from statistics alone. Here τ is the mean life and α is the rms deviation of the distribution of fluctuations in the π-μ time difference measurements. Since α is appreciably less than τ, the above factor does not differ sensibly from one.

The statistical error has been combined with the estimated systematic error, and the result for the π^+ mean life is

$$\tau_m = (2.53\pm0.10)\times10^{-8}\text{ sec.}$$

This value for τ_m is not in good agreement with the preliminary value $(1.65\pm0.33)\times10^{-8}$ sec reported previously. We are not aware of any systematic error in the earlier measurement as large as would apparently be necessary to account for this discrepancy. On the other hand, systematic errors were more carefully investigated in the present experiment, and the final result for τ_m given above has been evaluated using only the 670 π-μ decays from this experiment.

[7] Godfrey, Harrison, and Keuffel, Phys. Rev. **84**, 1248 (1951).

VII. UNRESOLVED π-μ DECAYS

There were a total of 1831 traces with acceptable e pulses, and 670 of these had μ-pulses with delays of 2×10^{-8} sec or greater. The calculated number of π-μ decays that occurred in the interval 0 to 2×10^{-8} sec is 800±40, the uncertainty arising from the uncertainty in the π^+ mean life. The total number of π-μ decays is therefore 1470±40, and it is interesting to inquire as to the origin of the remaining 360±40 traces which had e pulses but no μ's. There were several contributing effects as discussed below.

1. Accidentals

There were 12,200*AB–C* coincidences and 1831 of the resulting traces had at least an acceptable e pulse. Since the background rate of single pulses in counter B was about 1 per 750 microseconds, the calculated number of traces showing an accidental e pulse is 145.

2. Decay of $\pi^\pm$ Mesons in Flight

Some of the π-mesons produced in the CH_2 target decayed in flight, producing μ-mesons which could stop in counter B. Negative as well as positive mesons contribute here, since there is essentially no nuclear capture of negative μ-mesons in carbon. The probability that a π-meson produced in the CH_2 target (with energy and angle favorable for detection) would decay before stopping was 4.2 percent. This probability was almost independent of the meson energy at production. The contribution of $\pi^\pm$ mesons that decayed in flight is then $0.042\times1470\times(1+\gamma)$, where 1470 is the total number of π^+ mesons stopped in counter B and γ is the ratio of negative to positive mesons produced at the appropriate energy and angle in CH_2. Since the protons in a carbon nucleus are only $\frac{1}{3}$ as effective as free protons in producing π^+ photomesons,[8] and the ratio of π^- to π^+ production in carbon is about 1.4,[9,10] γ is about 0.7. The contribution of $\pi^\pm$ mesons that decayed in flight is then 102.

3. Mesons Coming to Rest in the Material Behind Counter B

The mesons produced in the CH_2 target had energies up to about 150 Mev. Some π^+ mesons, therefore, came to rest in the 0.37 g cm^{-2} of aluminum that separated the liquid of counter B from that of counter C. In general, the μ-meson from the decay of the π would not succeed in getting into counter B, but in about half the cases the electron from the decay of the μ would give an acceptable e pulse. This type of event contributed about 90 traces showing e but no μ-pulses.

4.

As mentioned in Sec. III, some events were rejected because the height of the μ-pulse was less than a

[8] J. Steinberger and H. A. Bishop, Phys. Rev. **78**, 494 (1950).
[9] Peterson, Gilbert, and White, Phys. Rev. **81**, 1003 (1950).
[10] I. Lebow, M.I.T. thesis (1951).

preassigned value. Those rejected for this reason alone comprised 3 percent of the total. Although only 670 π-μ decay times were 2×10^{-8} sec or longer, 900 were actually resolved, leaving 570 completely unresolved. Included then, among the 360 traces which had e pulses but no μ's, were 3 percent of 570 or 17 events that would have been rejected had it been possible to measure the μ-heights.

Also, π-heights corresponding to energy losses less than 10 Mev were rejected. Since it was not possible to measure the π-heights alone for the 570 unresolved π-μ decays, π-heights between 6 and 10 Mev were presumably accepted, whereas they would have been rejected had it been possible to measure the π-heights alone. The calculated number of these is 76.

Combining 1, 2, 3, and 4, we have $145+102+90+(17+76)=430\pm25$, the uncertainty arising mostly from uncertainty in the background rate of single pulses in counter B. This is seen to be in satisfactory agreement with the observed 360 ± 40 traces showing e pulses but no μ's. It would have been possible to reverse the above argument and to use the calculated number of unresolved π-μ decays as a part of the π^+ mean life evaluation. However, the mean life evaluation as it stands, does not, it is believed, contain systematic errors beyond those discussed. No such confidence could be placed in the above estimates, and it is felt that some contributing factors of importance could have been overlooked.

VIII. PULSE-HEIGHT DISTRIBUTION

Shortly after the experimental data were obtained, small scintillation counters connected in twofold coincidence were placed above and below counter B. Coincidences, caused by fast cosmic-ray μ-mesons that succeeded in penetrating the 10 cm of lead piled above the apparatus, triggered the oscilloscope associated with the counter B. The pulses resulting from the traversal of the counter by these mesons were photographed and the pulse-height distribution is shown in Fig. 6. The width of the distribution arose from photomultiplier statistics and the only fair geometry for light collection, and from fluctuations in the energy loss of

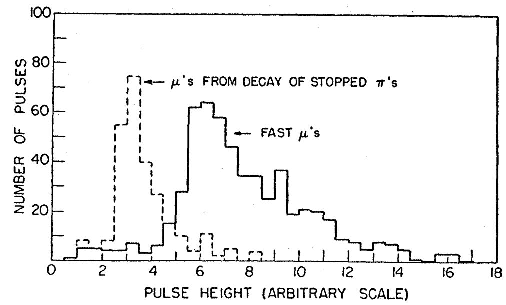

FIG. 6. Pulse-height distributions of μ-mesons from the decay of stopped π-mesons and of fast cosmic-ray μ-mesons.

the μ-mesons.[11,12] Also plotted in Fig. 6, is the distribution of μ-pulse heights as taken from a portion of the π^+ mean life data. Here the entire kinetic energy, 4.15 Mev, was expended in the liquid so the width of the distribution must be attributed to instrumental effects, such as photomultiplier statistics and light collection geometry, alone. If an energy scale is established by relating the average height of the cosmic-ray pulses to their calculated average energy loss (8.1 Mev), the average height of the pulses from the π^+ mean life data corresponds to an energy of 4.0 Mev. This is in good agreement with the known kinetic energy, 4.15 Mev, that a μ-meson receives from the decay of a π-meson at rest, and can be taken as an indication that the light output from a xylene-terphenyl solution per unit of energy lost is not a sensitive function of the specific energy loss over the range involved. For the cosmic-ray μ-mesons, $dE/dx=2.5$ Mev/g cm^{-2}, and 75 percent of the energy of a 4-Mev μ-meson is lost while $50>dE/dx>15$ Mev/g cm^{-2}.

It is a pleasure to acknowledge helpful discussions with Professor Bruno Rossi. Mr. W. B. Smith ably assisted with many of the electronic problems. A. Odian and L. Sartori spent many tedious hours examining film. The cooperation of the M.I.T. synchrotron staff is greatly appreciated.

[11] L. Landau, J. Phys. (U.S.S.R.) **8**, 201 (1944).
[12] K. R. Symon, Harvard thesis (1948).