Measurement of the Positive π-Meson Lifetime*

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(Received February 7, 1951)

The time intervals between the succession of events: stopping of a π^+ meson in a stilbene crystal, $\pi\rightarrow\mu$-decay and $\mu\rightarrow\beta^+$ decay are used to identify the pulses produced by π^+ mesons and to measure the mean life of the $\pi^+\rightarrow\mu$-decay. For this mean life we find $(2.58\pm0.14)\times10^{-8}$ sec.

INTRODUCTION

THE first evidence of the decay of a heavy (π) meson into a lighter (μ) meson was tracks in a photographic emulsion which had been exposed to cosmic rays by Lattes, Muirhead, Occhialini, and Powell.[1] From the length of time the heavy meson spent in the emulsion they set a lower limit on the lifetime as 10^{-11} sec.

Later, working with π-mesons produced artificially in the Berkeley 184-inch cyclotron, Lattes was able to establish an experimental lower limit of 5×10^{-9} sec for the lifetime. The first direct measurement of the π-meson lifetime was made by Richardson.[2] His method was to measure the fraction of negative π-mesons which survived various times of flight in the cyclotron vacuum tank. He detected the mesons by photographic plates and reported the mean lifetime of $(1.11_{-0.35}^{+0.45})\times10^{-8}$ sec. Later, Martinelli and Panofsky[3] using a technique similar to that of Richardson measured the mean lifetime of positive π-mesons. They found τ equals $(1.97_{-0.25}^{+0.21})\times10^{-8}$ sec.

In the light of recent developments in electronic techniques it was natural to plan experiments to determine the lifetime of the π-mesons by means of electronic detectors because of the expected improvement in accuracy over previous methods. A classic example of electronic technique for the measurement of a mean lifetime in the microsecond region is that of Rasetti's[4] work on "slow mesons," which are now identified as μ-mesons.

A preliminary measurement of the positive π-meson lifetime using a method similar to the one presently described was reported by Kraushaar, Thomas, and Henri.[5] On the basis of 57 $\pi\rightarrow\mu$-decays they obtained for the mean lifetime $(1.65\pm0.33)\times10^{-8}$ sec.

More recently at this laboratory Jakobson, Schulz, and Steinberger[6] measured the mean lifetime of positive π-mesons in connection with the development of improved apparatus for electronic detection and counting of π-mesons. They found $\tau=(2.54\pm0.11)\times10^{-8}$ sec based upon the results of counting 5641 mesons.

The present paper describes in more detail the work reported by Chamberlain, Mozley, Steinberger, and Wiegand.[7]

EXPERIMENTAL METHOD

The 322-Mev (maximum) x-ray beam of the Berkeley synchrotron was used to produce π-mesons in a target of polyethylene. Figure 1 is a diagram of the arrangement of the apparatus. The x-ray beam was collimated by lead shielding to produce a beam 1 inch in diameter incident upon the polyethylene target, which was in size and shape a 2-inch cube. The detectors consisted of two crystals of *trans*-stilbene arranged to form a counter "telescope" at right angles to the beam. The phosphorescent radiation caused by an ionizing particle which passed through either of the crystals was detected by multiplier phototubes associated with each crystal. The entire apparatus was surrounded by lead shielding 6 to 8 inches thick. Each crystal measured 4.5×4.1 cm and was 1.8 cm thick. An aluminum absorber 1 inch thick was placed between the target and the detectors in order to reduce the energy of the emitted mesons. This had the effect of increasing the probability that a meson would stop in the crystal detector.

The object of this experiment was to determine the

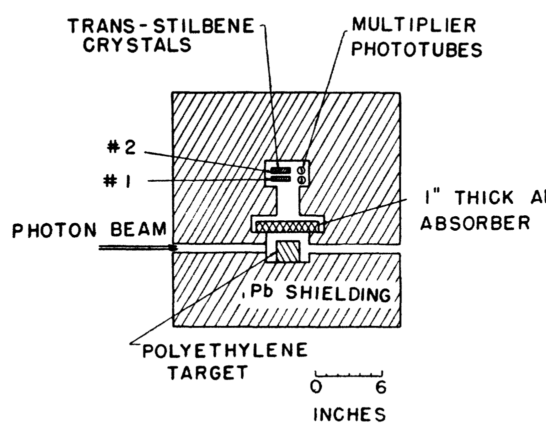


FIG. 1. Schematic diagram of the arrangement of the detecting apparatus.

* This work was performed under the auspices of the AEC.
† Submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy.
[1] Lattes, Muirhead, Occhialini, and Powell, Nature **159**, 694 (1947); **160**, 486 (1947).
[2] J. Richardson, Phys. Rev. **74**, 1720 (1948).
[3] E. A. Martinelli and W. K. H. Panofsky, Phys. Rev. **77**, 465 (1950).
[4] F. Rasetti, Phys. Rev. **59**, 706 (1941); **60**, 198 (1941).
[5] Kraushaar, Thomas, and Henri, Phys. Rev. **78**, 486 (1950).
[6] Jakobson, Schulz, and Steinberger, Phys. Rev. **81**, 894 (1951).
[7] Chamberlain, Mozley, Steinberger, and Wiegand, Phys. Rev. **79**, 394 (1950).

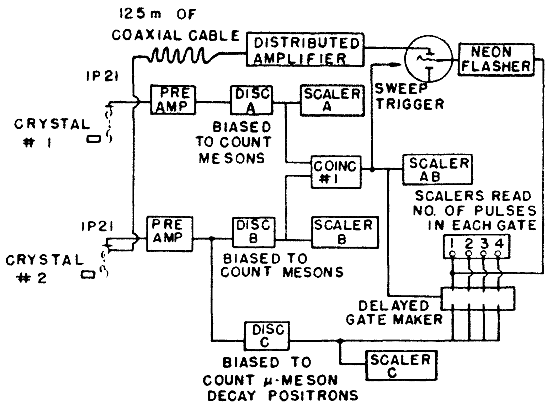


FIG. 2. Block diagram of the electronic apparatus.

mean lifetime of positive π-mesons by measurement of the time intervals between the stopping of π-mesons and the emission of μ-mesons. In order to be certain that the observed pulses were due only to π-mesons, the μ-decay positrons were detected and recorded by an apparatus developed by Steinberger.[8] The time intervals corresponding to the lifetime of the π-mesons were measured by recording photographically the pulses from the second crystal detector displayed on the screen of a cathode-ray oscillograph.

APPARATUS

A block diagram of the electronic apparatus is presented in Fig. 2. The design of the electronic components was for the most part based upon standard techniques employing resistance-capacitance coupling and high transconductance miniature tubes to obtain sufficiently rapid response in the coincidence and gate-forming circuits. However, sufficient resolution of the π- to μ-decay pulses requires a vertical deflection amplifier

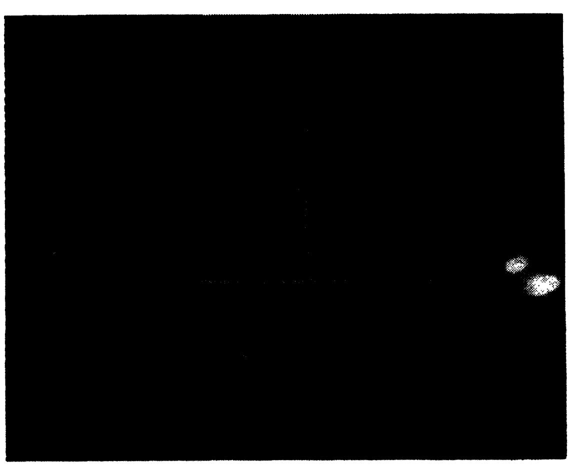


FIG. 3. Photographic reproduction of a typical oscillograph trace showing the π-μ-meson decay pulses and the neon flash bulb marking. The pulse separation is about 4×10^{-8} sec.

[8] J. Steinberger and A. S. Bishop, Phys. Rev. **78**, 493 (1950).

capable of producing pulses which have a time of rise of 10^{-8} sec or less. The deflection amplifier used in this experiment made use of the traveling wave concept and its design was based upon principles discussed by Ginzton, Hewlett, Jasberg, and Noe[9] in their paper on distributed amplification. The time of rise of the oscillograph deflection system was about 5×10^{-9} sec. The amplifier was operated with a gain of 15.

Let us review the electronic events due to the detection of a π-μ-decay: If a meson passed through crystal number 1 and stopped in number 2 and the pulses were accepted by discriminators A and B, there was produced at the output of coincidence number 1 a pulse which started the sweep and intensifying circuits of the oscillograph for π-μ-decay and at the same time initiated a circuit which opened a series of four delayed gates beginning 0.5 μsec later for μ-β^+ decay. The length of the delayed gates was 2×10^{-6} sec. On account of its limited resolution, coincidence number 1 treated the two pulses from the stopping of the π-meson and the emission of the μ-meson as one event. The output of detector number 2 was also connected to another discriminator, C, biased to accept μ-meson decay positron pulses. If a particular pulse were accepted by discriminator C, it was fed to the delayed gate circuit; and, if a gate were open, the pulse was recorded by the register associated with the open gate. When a pulse was recorded in the first delayed gate, an additional circuit was actuated and caused a small neon lamp to flash momentarily. The neon lamp was placed near the face of the oscillograph tube and in the field of view of the recording camera. Its flash would thus produce a dot on the film at the end of the sweep trace. The dot appearing at the end of the trace would then indicate that the pulse of the positron from the μ-meson decay had been detected. A third connection to detector number 2 was made to a section of 125 ohms impedance RG 63/U coaxial cable 125 meters long and thence to the distributed amplifier, the output of which was connected as directly as possible to the vertical deflection plates of the oscillograph. The purpose of the long cable was to delay the pulse about 0.5 microsecond in order to allow the oscillograph sweep and intensifier circuits to become operative. The sweep duration was 0.8×10^{-6} sec. The oscillograph trace thus displayed the pulses which occurred in detector number 2 during a time interval of about 0.8×10^{-6} sec after the passage of a particle through detector number 1 and into or through number 2. Figure 3 is a reproduction of a typical trace.

The sweep speed of the oscillograph was calibrated by applying a sine wave voltage of known frequency to the vertical deflection plates. Such calibrations were made several times during the course of the experiment. The standard frequency source was a General Radio type 605-B signal generator accurately calibrated

[9] Ginzton, Hewlett, Jasberg, and Noe, Proc. Inst. Radio Engrs. **36**, 956 (1948).

to within ±0.3 percent. Also, we allowed a slight amount of extraneous pick-up from the synchrotron radiofrequency system which provided a practically continuous calibration by its presence on the pulse base line. The frequency of the synchrotron was constant and by a different signal generator was found to be 47.34±0.02 megacycles per second. The two measurements agreed and showed the sweep speed to be linear within ±0.5 percent and to amount to 1.3×10^{-8} sec mm^{-1} at the screen of the cathode-ray tube.

The apparatus was adjusted by trial to give a reasonable rate of traces exhibiting π-μ-decay pulses and at the same time a reasonably low background of spurious traces. A typical run was as follows: During a $1\frac{1}{2}$-hour exposure the standard length of 100 feet of film was run continuously through the camera, and there were recorded upon this film 5232 traces of which 168 bore the neon lamp flash marker.

A microfilm reader was used to examine the processed film. Images of the traces were projected onto a piece of graph paper upon which the distance between two pulses could easily be determined to within 1 mm. With the particular camera and projector arrangement employed, 1 mm on the projector screen represented 0.362×10^{-8} sec.

The distance between pairs of pulses was interpreted as indicated by Fig. 4. Points halfway up the leading slopes were determined, and the distance between pulses was taken to be the distance between the projections upon the base line of these two points. All double pulses marked by the flash were included in the tabulation of the data. Only in a very few instances was it questionable that a pulselike disturbance on the baseline was due to a μ-meson. The heights of the μ-meson pulses were fairly uniform, as is indicated by a plot of the number of pulses *versus* their height in Fig. 5.

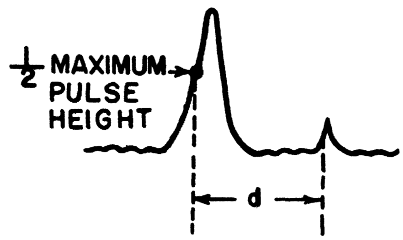
The slope of the baseline due to the first pulse influences the apparent height of the second pulse and this accounts largely for the small pulses of Fig. 5. However, the time separation was not affected, since the distance between the pulses was measured using the middle of the rise as illustrated in Fig. 4. Furthermore, since the amplifier was always operated well within its linear region, we believe there was no distortion by the amplifier of the pulse separation times.

Considering all the traces marked by the neon flash bulb, it was not possible in every instance to observe two distinct pulses. This was interpreted as being due to π-meson decays occurring within the resolving time of the system and, consequently, the stopping of the π-meson and emission of the μ-meson appearing as one pulse. The treatment of such unresolved decays will be discussed later.

RESULTS

During the course of the experiment a total of 1419 separate traces marked with the neon flash bulb were accumulated. A total of 691 of the marked traces

Fig. 4. Illustration of the method of measuring the separation *d* between two pulses.



exhibited two clearly separated pulses between which the distance could be measured, and the remainder were unresolved. The distances between the pairs of pulses were tabulated to the nearest millimeter on the projector screen. A histogram of the number of pulses which occurred with various time separations is presented in Fig. 6.

An integral representation of the same data is given in Fig. 7 in which the total number of pulses occurring after a certain time is plotted as a function of this time upon semilogarithmic paper. This number is given by $N(t)=N_0e^{-\lambda t}$, where N_0 is the total number of recorded traces due to π-mesons stopping in the detector and λ is the meson decay constant.

In Fig. 8 the data are shown in differential form, where the logarithm of ΔN, the number of pulses occurring in the constant time interval 1.45×10^{-8} sec, is plotted *versus* time. The expression τ is the time for ΔN to diminish by the factor $1/e$ and by inspection of the curve is seen to amount to about 2.6×10^{-8} sec.

a. Analysis of Differential Curve

Inspection of the histogram Fig. 6 and the integral curve Fig. 7 reveals that apparently all of the π-μ-decay pulses were resolved after 2.17×10^{-8} sec. Therefore, only pulses which occurred after 2.17×10^{-8} sec

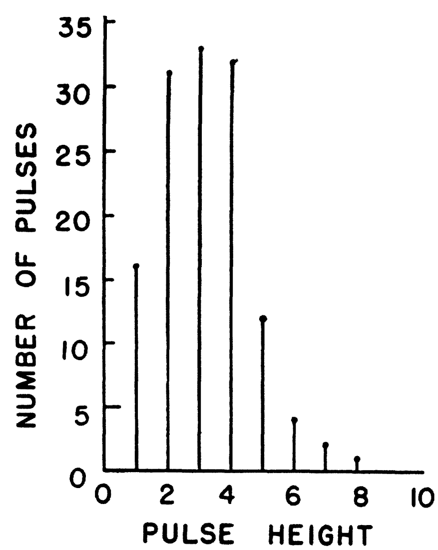


Fig. 5. Histogram of the number of μ-meson pulses *versus* the height of the pulses.

(554 in number) are included in the lifetime calculation and the differential decay curve, Fig. 8.

As far as one can tell from the decay histogram of Fig. 6, the background of pulses from extraneous phenomena was negligible. The one pulse which occurred at 25.3×10^{-8} sec is reasonably expected from a pure radioactive decay. The interval (26 to 36)$\times 10^{-8}$ sec, during which the delayed gate was known to be closed, contained no pulses. Using the known counting rate in scaler C and the beam on time, it is calculated that there should be a probability of 0.3 of getting one accidental pulse in the accepted time interval of the whole experiment.

A different background arising from mesons stopped in detector 2 and accompanied by an accidental pulse in the first delayed gate and flashing the neon bulb is calculated to be 0.6 of one pulse during the whole experiment. This latter background would arise only in cases in which the π-μ-decay occurred too quickly to be resolved and the μ-β^+ decay occurred within 25.3 $\times 10^{-8}$ sec. Allowing for a background of one pulse out of the 554 decays will require a correction to the mean lifetime of -0.02×10^{-8} sec.

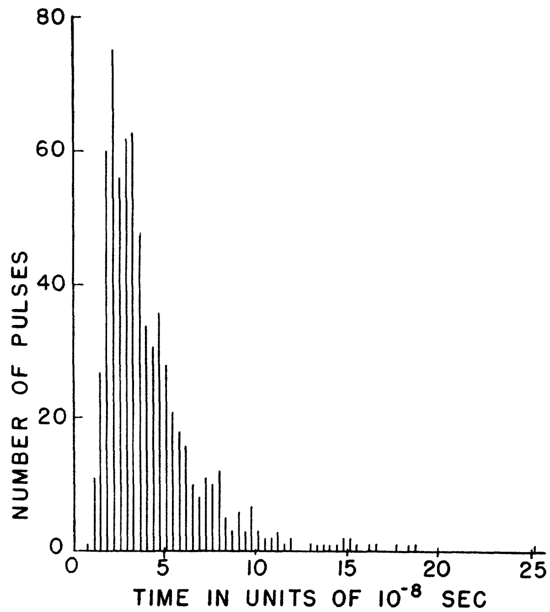


FIG. 6. Histogram of the number of measured pulse pairs *versus* the time of their separation.

The mean lifetime is given by

$$\tau=\textstyle\sum_i N_it_i/\sum_i N_i,$$

where N_i is the number of π-mesons which decay in the ith time interval and t_i is the time from a suitably chosen origin to the center of the ith interval.

The summations should include all pulses occurring after the chosen time origin. (We have included those from 2.17×10^{-8} through 25.34×10^{-8} sec.) The correction due to exclusion of all pulses after 25.34×10^{-8} sec has been calculated and is negligible (-0.1 percent error). The error due to taking finite time intervals is also negligible ($+0.16$ percent).

Since not all of the pulses were resolved until after the sixth interval of 0.362×10^{-8} sec, we have chosen as time 0 the center of the sixth interval. We have then

$$\tau=\sum_{i=6}^{70} N_it_i \Big/ \sum_{i=6}^{70} N_i,\quad \tau=2.65\times 10^{-8}\text{ sec.}$$

The statistical error in the result for τ is obtained by a method pointed out by Peierls.[10] The percentage error in τ is given by $1/\sqrt{N}$, where N is the number of measured pulses used (554):

$$\tau=(2.65\pm 0.11)\times 10^{-8}\text{ sec.}$$

A correction for a systematic error and a discussion of the reliability of the measurements will be given later.

b. Analysis of the Integral Curve

The integral representation of the data allows us to make use of the unresolved pulses in the first few time intervals providing we know the total number of mesons which stopped in the detector. This procedure gives a point of high statistical accuracy and is important in determining the slope of the decay line. However, it may be reduced in effectiveness by the uncertainty of the necessary corrections for background.

Of the 1419 recorded traces marked by the neon bulb, 691 showed two resolvable pulses leaving 728 unresolved single appearing pulses. However, not all the unresolved pulses were due to π-mesons stopped in the detector because there was a background of spurious pulses which could fall within the delayed gate time, initiate the flash bulb, and thus give false impressions of arising from μ-meson decay positrons. Another source of single background pulses originated from the decay of π-mesons while in flight from the polyethylene target to the detectors. Such events could lead to μ-mesons coming to rest in the detector and making single pulses, and then their decay positrons activating the neon bulb flasher.

An estimate of the number of spurious unresolved pulses can be made as follows: If all the pulses arriving at the delayed gates are due to positrons from μ-meson decay, they should accumulate in the four gates according to the law $N_i=N(0)\exp(-\lambda\mu t_i)$ ($i=1, 2, 3, 4$), where t_i is the time at the center of the gate. A departure from this law can be attributed to the background. If we assume $\lambda_\mu=4.65\times 10^5$ sec^{-1} ($\tau_\mu=2.15\times 10^{-6}$ sec) and attempt to fit the expected curve to the experimental data, we find that a background of about 5 percent of the total number of pulses must be subtracted.

Another calculation of the background pulses falling into the delayed gates and flashing the neon bulb can

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

be made from the auxiliary counters indicated on the block diagram of Fig. 2. The number of gates made was equal to the number of pulses in coincidence accepted by discriminators A and B and registered in scaler AB. The number of pulses which could fall into a delayed gate was the number accepted by discriminator C and registered in scaler C. Then, if τ was the time in seconds that a gate remained open each time it was made and T was the time during which the number of counts N_{AB} and N_C were accumulated, the number expected to randomly fall into a gate is given by

$$N_{\text{accid}}=N_{AB}N_C\tau/TF,$$

where F is the fraction of time the synchrotron beam was actually on and is sometimes referred to as the duty cycle. The beam pulses came at a rate of 6 per second and had a duration of about 2×10^{-3} sec. Hence,

$$F=1.2\times10^{-2}.$$

A typical run lasted 87 minutes, during which 4217 pulses were received in scaler AB and 73,820 in scaler C. The value of τ was 2×10^{-6} sec for each of the four delayed gates. Putting these values into the formula, we find the expected number of accidentals to be 9.94.

During this run 160 pulses were registered in the first delayed gate. If then 10 of these were background, as we have just computed, 10/160 or about 6 percent of the pulses were accidental; and this agrees within statistical accuracy with the previously estimated value. The average background of spurious unresolved pulses for the entire experiment came to 7 percent of the total number of pulses marked by the neon flash bulb.

The second correction needed to establish the total number of stopped π-mesons is obtained by evaluating the fraction of π-mesons which decayed in flight from the target to the detector. The kinetic energy of the emitted π-mesons lies in the region of 60 Mev and their rest energy m_0c^2 is about 140 Mev. Then, it follows that $v/c=0.72$, where v is the velocity of the meson and c is the velocity of light. Since the energy of the emitted mesons is not constant, it will be sufficient to consider the velocity constant during the flight. The probability that a meson decay while traversing the distance $d=20$ cm from the target to the detector is

$$(1-v^2/c^2)^{\frac{1}{2}}d/\tau v=0.025,$$

where τ is the approximate mean lifetime. We have finally a background of about 10 percent to subtract from the total number of recorded traces marked by the neon flasher. This leaves 1277 pulses for the first point on the integral curve.

The data of the integral representation can be conveniently analyzed by calculating the average lifetime of the unresolved pulses and combining this point with the differential curve. The average lifetime τ' of the unresolved pulses can be expressed as follows:

$$\tau'=\frac{\int_0^T \lambda e^{-t/\tau}t\,dt}{\int_0^T \lambda e^{-t/\tau}dt}=\tau\left[1+\frac{T/\tau}{1-e^{T/\tau}}\right],$$

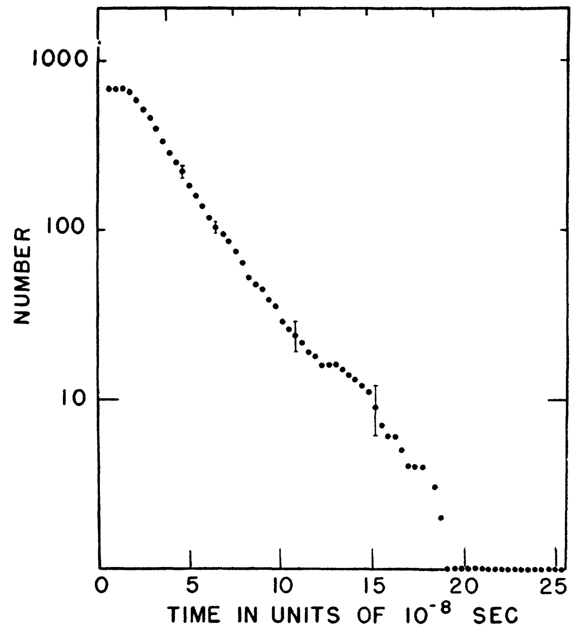


FIG. 7. Plot of the total number of pulses occurring after a certain time *versus* this time.

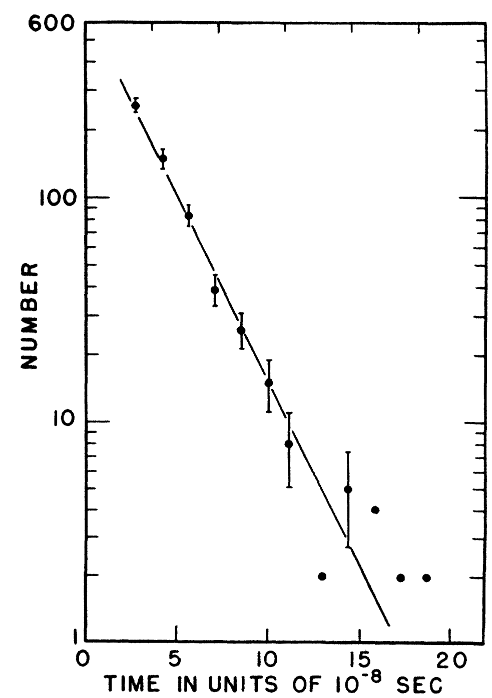


FIG. 8. Plot of the number of pulses occurring in time intervals of 1.45×10^{-8} sec *versus* the time.

TABLE I. Experimental uncertainties and estimates of their contributions to the error.

Uncertainty	Estimated relative errors Differential data	Integral data
Measurement of pulse separations	±0.02	±0.02
Sweep calibration	±0.005	±0.005
Nonlinearity of sweep	±0.005	±0.005
Number of unresolved pulses		±0.04
Statistics (standard deviations)	±0.043	±0.028
Total errors	±0.048	±0.053

where $\tau=2.65\times10^{-8}$ sec is the mean lifetime obtained from the differential curve and the time T for the pulses to be fully resolved is 2.17×10^{-8} sec. Then, it follows that

$$T/\tau=0.82, \quad \tau'=0.91\times10^{-8} \text{ sec.}$$

To combine this information with the differential data we subtract the 554 resolved pulses used in the differential curve from the total of 1277, leaving 723 unresolved pulses N_s. We must insert another term, $N_i\times2.17\times10^{-8}$ sec, in the numerator of the mean lifetime relation, so that the origins of the time scales will coincide. Finally, the mean lifetime including the unresolved pulses is given by

$$\tau=\sum N_it_i+6\times0.352\times10^{-8}\times N_i/\sum N_i+N_s = 2.60_5\times10^{-8} \text{ sec.}$$

In the above analysis a total of 1277 measurements are involved, so that if we apply Peierls' method of determining the error, we find a standard deviation of ±2.8 percent, or

$$\tau=(2.60_5\pm0.07)\times10^{-8} \text{ sec.}$$

The actual standard deviation is somewhat larger, because we do not know the exact time at which the unresolved pulses occurred, whereas in Peierls' analysis it is assumed that the time at which each pulse occurred is known exactly. It is easy, however, to see that this addition to the standard deviation under our experimental conditions is small compared to the term $1/\sqrt{N}$.

A systematic error which caused an apparent lengthening of the mean lifetime arose as follows: The gate which allowed the μ-meson decay positron to be detected was initiated by the stopping of π-mesons, whereas to be consistent in allowing a constant fraction of decay positron pulses to fall within it, the gate should have been initiated by the μ-meson pulses. Consequently, the longer a π-meson lived in the detector, the higher was the probability that its μ-meson decay positron pulse would fall within the delayed gate and actuate the neon flash circuit. A detailed calculation shows that our arrangement actually measured the difference between the decay constants of the π- and μ-mesons.

We have found the π-meson decay constant to be approximately 3.85×10^7 sec^{-1}. The μ-meson decay constant is 4.65×10^5 sec^{-1}. Therefore, the effect of the above correction is to reduce the measured mean lifetimes by 1 percent.

There are uncertainties in all the operations involved in the tabulation of the data. For instance, it is possible that the distances between the pairs of pulses have been on the average over- or underestimated. The sweep calibration could not be determined exactly and there was a slight nonlinearity in the sweep speed. The number of unresolved pulses involved the fraction of time the synchrotron emitted its photon beam. This duty cycle was not accurately known and probably was not constant.

Various uncertainties and estimates of their contributions to the error are listed in Table I.

We have found from the differential data $\tau=2.65\times10^{-8}$ sec and from the integral data $\tau=2.60_5\times10^{-8}$ sec. Then, subtracting one percent for the systematic correction and 0.02×10^{-8} sec for background effects and applying the above errors, we find the final results of this measurement of the mean lifetime of positive π-mesons:

$$\tau=(2.60\pm0.13)\times10^{-8} \text{ sec (differential data),}$$

$$\tau=(2.56\pm0.14)\times10^{-8} \text{ sec (integral data),}$$

and correspondingly for the half-life:

$$T_{\frac{1}{2}}=(1.80\pm0.09)\times10^{-8} \text{ sec,}$$

$$T_{\frac{1}{2}}=(1.77\pm0.10)\times10^{-8} \text{ sec.}$$

The author gratefully acknowledges the considerable assistance of Dr. Owen Chamberlain, Dr. R. F. Mozley, and Dr. J. Steinberger in analyzing the photographic records. The incorporation of Dr. Steinberger's meson-detecting equipment into the apparatus greatly accelerated the progress of the experiment. Thanks are extended to Professors E. McMillan and E. Segre for their encouragement and many helpful discussions. The cooperation of the synchrotron operating staff is deeply appreciated.

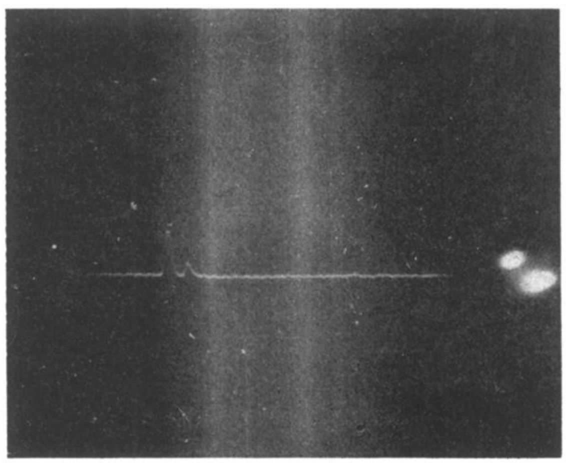


FIG. 3. Photographic reproduction of a typical oscillograph trace showing the π-μ-meson decay pulses and the neon flash bulb marking. The pulse separation is about 4×10^{-8} sec.