COMPARISON OF PION AND ANTIPION LIFETIMES*

M. Bardon, U. Dore,† D. Dorfan, M. Krieger,‡ L. Lederman, and E. Schwarz§

Columbia University, New York, New York
(Received 23 March 1966)

It is now known that weak interactions are not invariant under space inversion, P, and particle-antiparticle conjugation C. It has also been observed that CP invariance is violated in $\Delta S=1$ nonleptonic decay.[1]

In fact, experimental support for CPT invariance[2] of leptonic $\Delta S=0$, weak interactions is relatively poor. Tests of CPT invariance are based on the following theorem:

If H_{wk} is CPT invariant, then to all orders in the weak interaction, particle and antiparticle masses are equal, and to first order in H_{wk}, the total decay rates are equal. In the case that the final-state particles interact only weakly, partial decay rates are also equal.[3]

Earlier results in this laboratory have established the ratios

$$\tau(\pi^+)/\tau(\pi^-)=1.00\pm0.08,\quad \Delta S=0,\ \text{semileptonic},^4$$

$$\tau(\mu^+)/\tau(\mu^-)=1.000\pm0.001,\quad \Delta S=0,\ \text{leptonic}.^5$$

We have remeasured the ratio of π^+ to π^- lifetimes. We find

$$\frac{\Gamma(\pi^+\to\mu^++\nu_\mu)}{\Gamma(\pi^-\to\mu^-+\bar{\nu}_\mu)}=1.004\pm0.007. \tag{1}$$

The method is based upon the detection of π-μ decays in flight for pion beams of ~120 MeV/c extracted from the Nevis cyclotron. The experiment arrangement is shown in Fig. 1. The essential idea is to select a very small and geometrically well-defined slice in phase space from the broad spectrum of pions deflected into the beam channel by the cyclotron fringing field. A 2-m long decay region is defined by carefully constructed veto counters and filled with helium gas to reduce to a minimum the possibility of a scattering background to the π-μ counts.

Beam momenta and directions are defined by counters S_1 and S_2 (located inside the shielding enclosure to give a long time-of-flight path), by a slit in front of dipole M, by counters S_3 and S_4, and by the circular apertures

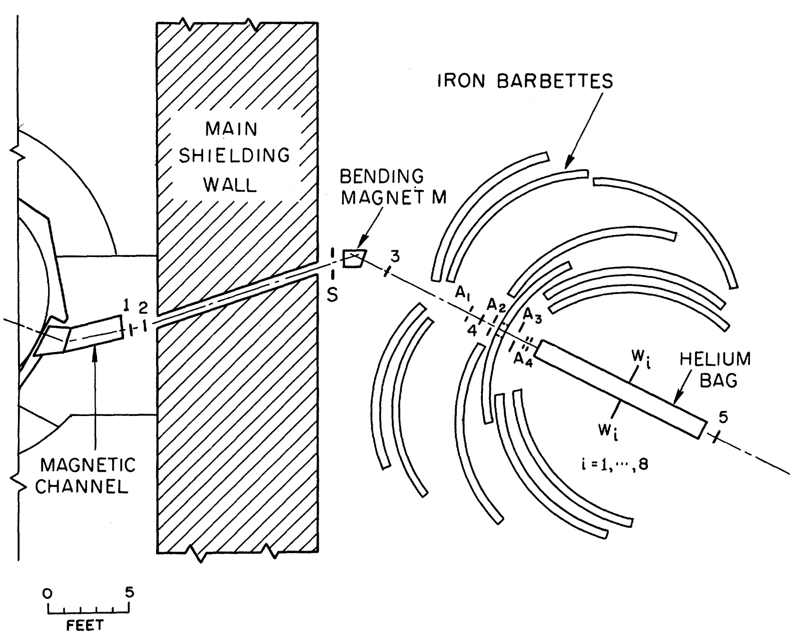

FIG. 1. Layout of the experimental apparatus.

in veto counters A_1, A_2, A_3, and A_4. The beam dimensions were 2 in.×2 in. as defined by counters and apertures.

The beams contain varying compositions of pions, muons, and electrons. Pions are identified by time of flight (TOF) between S_2 and S_4 (~35 nsec for $\beta=0.66$). We define as "π" particles which satisfy the logic requirement $S_1S_2S_3S_4\bar{A}_1\bar{A}_2\bar{A}_3\bar{A}_4$ and whose TOF lies in a window between two fixed values. Figure 2(a) shows a time spectrum for the negative beam, and Fig. 2(b) shows the effects of gating with the "π" signal.

Muons are detected in an annular array of eight counters, W_1-W_8. These have axial symmetry and permit a check of the azimuthal symmetry of the muon yield. A "$\pi\mu$" event is a prompt (20 nsec) coincidence of a "π" and any count in W. The ratio of decay rates is obtained by comparing the ratios "$\pi\mu$"/"π", after corrections, for both sign of particles.

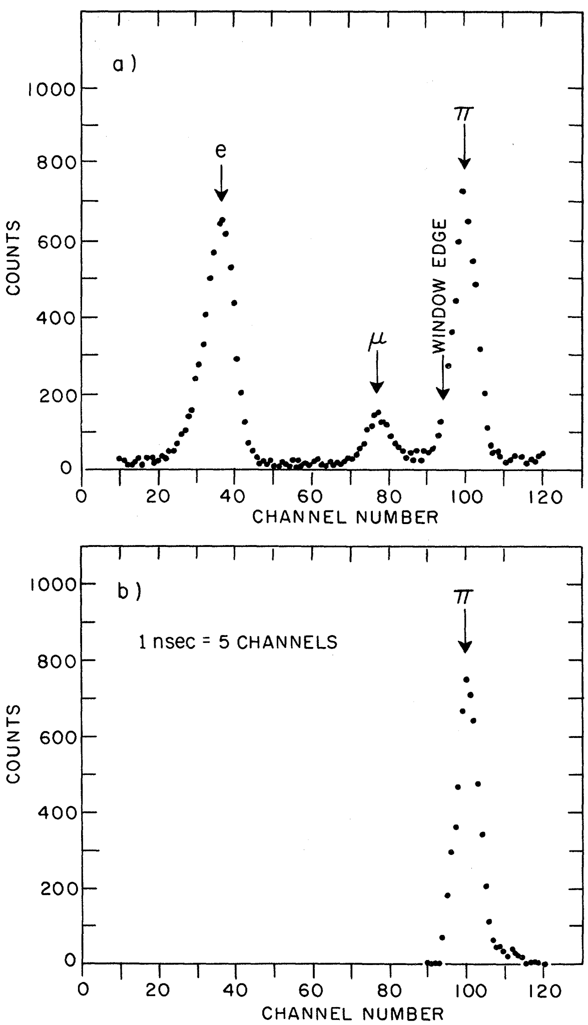

FIG. 2. (a) S_2-S_4 time-of-flight spectrum. (b) S_2-S_4 time-of-flight spectrum of particles chosen as "π."

Once the detection geometry is fixed and invariant to $\pi^+ \to \pi^-$, it remains to establish that (a) the beam momenta and spatial properties are the same; (b) the residual beam impurities are accounted for; (c) random coincidences and backgrounds are properly subtracted; (d) the "muon" counts are indeed from π-μ decay in the prescribed region.

Possible systematic drifts in electronic detection efficiencies are minimized by frequent cycling between π^+ and π^- runs, the crucial magnet field M being reset with a proton resonance probe and regulated to 0.05%. Background and accidental events were monitored simultaneously or after each run of a given polarity. The data are based upon ~4×10^5 pions of each sign taken at a counting rate of the order of 3 π's/sec. We now discuss the enumerated items in order.

(a) Beams.—To sufficient order, one only needs to establish that the momentum distributions are symmetric and that they have the same mean momentum. This was done in three independent ways, each involving different systematic effects at the level of some tenths of a percent.

(i) Pions, selected by the S_2-S_4 TOF window, which reached counter S_5 traversed a distance of ~12 m from counter S_2. The TOF (~60 nsec) was determined to $\pm\frac{1}{3}$ nsec by comparing it with the TOF of electrons present in the beam [see Figs. 3(a) and 3(b)]. The flight path was known to a precision of 2 in. This yielded the result

$$|\langle p^+\rangle - \langle p^-\rangle| / \langle p^+\rangle \leq 0.007.$$

(ii) Range curves were taken in both beams at the position following A_4 [Figs. 4(a) and 4(b)]. Due to different end-of-range behavior these were done in different ways: The π^+ were stopped in a $\frac{1}{8}$-in. counter followed by a veto; the π^- range was taken using successively higher settings of the stopping counter discriminator. An analysis of these curves shows the ranges to be identical to ±0.05 in. out of a range of 2.85 in. From an analysis of proton spectra from π^- carbon stars,[6] it appears that the range extension due to these is about the same as that due to $\pi^+ \to \mu^+$ decay in the scintillator.

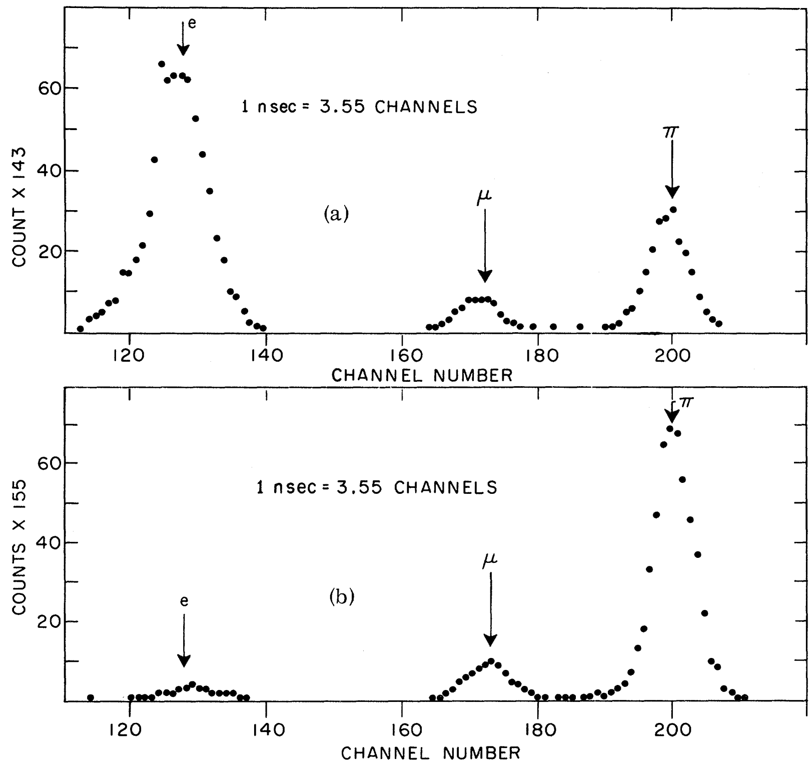

FIG. 3. (a) S_2-S_5 time-of-flight beam spectrum positive. (b) S_2-S_5 time-of-flight beam spectrum negative.

This again yields

$$|\langle p^+\rangle - \langle p^-\rangle|/\langle p^+\rangle \leq 0.007.$$

We can also determine the absolute momentum from these two measurements. We find $p_\pi = 122.0 \pm 0.7$ MeV/c with a width of 5 ± 2 MeV.

(iii) Beam profiles were taken at the entrance to the magnetic field and at counter S_5. Positive and negative profiles were indistinguishable although a shift of ~1 in. in peaks would have been detected. A shift of mean momentum of 1 MeV/c would correspond to >3 cm at S_5. The beam profile result yields

$$|\langle p^+\rangle - \langle p^-\rangle|/\langle p^+\rangle \leq 0.002.$$

(b) Impurities.—The residual beam impurities are only muons unresolved in the TOF system or pions which decay forward before counter S_3. The muon tail under the pion peak accepted, obtained from an unfolding of the S_2-S_4 TOF spectrum, is ~0.2%, and to a high order is the same for π^+ and π^-.

(c) Corrections.—There are two corrections to "π" to obtain the true number of accepted pions. (i) There is only one significant random rate, that between S_1S_2 and S_3-S_4 due to the high singles rates in S_1 and S_2. The events

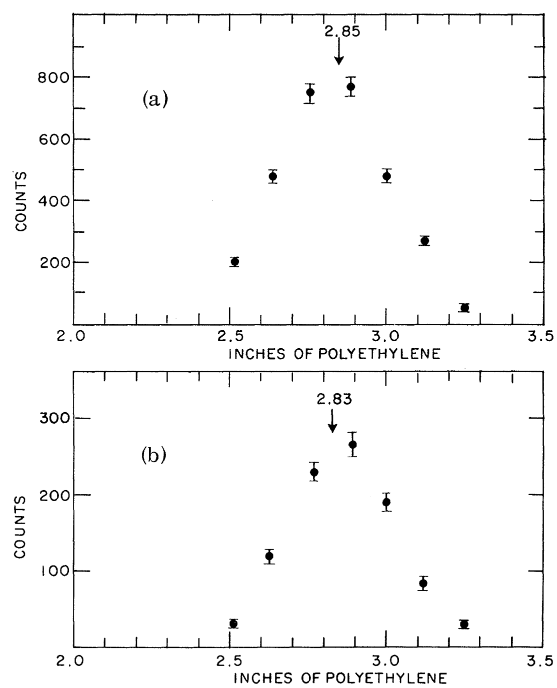

FIG. 4. (a) Range curve of positive "π." (b) Range curve of negative "π."

show up as a flat background in the S_2-S_4 TOF spectrum and so a certain fraction are accepted as "π." The correction (S_1S_2 del) is determined by recording "π" and "$\pi\mu$" with 100 nsec of delay in the S_1S_2 line. (ii) Some pions interact in counter S_4 ($\frac{1}{8}$ in.) and a small fraction have secondaries which fail to trigger any of the subsequent vetoes. This number is most efficiently obtained by periodically inserting a veto counter at the aperture of A_4 ("T-in"). The data for these corrections to "π" also provide corrections to "$\pi\mu$" and these are shown in Table I.

(d) Muon Counts.—The muon counters, W, are placed so that the only beam particles which can reach W are those which undergo scattering in the edges or wrapping of the veto counters or which scatter or decay in the helium which follows A_4. Since π^+ and π^- are known to scatter differently at these momenta (due to Coulomb-nuclear interference), this is a potentially dangerous point. Consequently, the total amount of scattering material (air, Mylar, helium) in the beam near A_4 was held to 0.06 g/cm^2. Estimates indicate that the resulting nuclear scatterings are negligible. These were confirmed by increasing the amount of material near the anti counters by a factor of 50 and measuring the resulting "$\pi\mu$'s." When the (nonlinear) multiple scattering effect of the added material is accounted for, we confirm that the effects of the 0.06 g/cm^2 are negligible in the relative rates and contribute ~0.3% to the absolute decay rate.

The efficiency of the muon counters also depends on the radial profile of the pion beam. Profiles permit a maximum difference of efficiency for μ^+ vs μ^- of less than 0.3% as determined from a Monte Carlo program.

Table I. Data and subtractions in thousands of counts.

	π^+	π^-
"π"	401.710	430.810
S_1S_2 del	10.7	16.0
T-in	1.9	10.3
Total corrected	12.6	26.3
"π" corrected	389.1	404.5
"$\pi\mu$"	54.9	57.7
S_1S_2 del	0.4	0.6
T-in	0.2	0.5
Total corrected	0.6	1.1
"$\pi\mu$" corrected	54.3	56.6
"$\pi\mu$"/"π"	0.1397 ± 0.0007	0.1403 ± 0.0007

The results in Table I are derived from 18 alternations of sign, each lasting about 7 hours. These give the final result presented above, Eq. (1), and serve to confirm the TCP prediction of equality of π^+ and π^- lifetimes with about 10 times the previous sensitivity.

As a final check, we can compute the absolute lifetime of the positive pion, given the spatial and momentum dispersion and the geometry of the counters. A Monte Carlo program was written to do the integrations, parametrized only by an unknown lifetime. This gives the result

$$\tau^+ = 25.6 \pm 0.3 \text{ nsec.} \tag{2}$$

In Eq. (2), the error is a combination of the 0.5% statistical error with a 0.6% uncertainty representing lack of knowledge of the absolute geometry and a 0.6% error in absolute determination of beam momentum. Several smaller uncertainties also enter the absolute rate but are negligible in the comparison. This is to be compared with recent measurements of the π^+ lifetime.[7]

The authors wish to thank Dr. J. Eades and Dr. M. Giannini for their help in the early stages of this experiment. Two of us, E. S. and U. D., would like to thank the Nevis Staff for the hospitality extended to us in this laboratory. We are grateful to Professor D. Caldwell for keeping us informed about an experiment with similar objectives being carried out at Lawrence Radiation Laboratory.

*Research supported in part by the Office of Naval Research No. Nonr-266 (72).

†On leave from Istituto di Fisica dell'Università Roma and Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Roma, Italia.

‡National Science Foundation Predoctoral Fellow 1966.

§Partial support from Swiss National Fund for Scientific Research.

[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

[2]W. Pauli, Niels Bohr and the Development of Physics (Pergamon Press, London, 1955); J. Schwinger, Phys. Rev. 82, 914 (1951); 91, 713 (1953); G. Lüders, Ann. Phys. (N.Y.) 2, 1 (1957).

[3]T. D. Lee, R. Oehme, and C. N. Yang, Phys. Rev. 106, 340 (1957); G. Lüders and B. Zumino, Phys. Rev.

106, 385 (1957).

[4]L. M. Lederman, H. Byfield, and J. Kessler, Phys. Rev. 85, 719 (1952); R. P. Durbin, H. H. Loar, and W. W. Havens, Phys. Rev. 88, 179 (1952).

[5]S. L. Meyer, E. W. Anderson, E. J. Bleser, L. M. Lederman, J. E. Rothberg, and I. T. Wang, Phys. Rev. 132, 2693 (1963).

[6]P. Amiraju and L. M. Lederman, Nuovo Cimento 4, 283 (1956).

[7]J. Ashkin, T. Fazzini, G. Fidecaro, Y. Goldschmidt-Clermont, N. H. Lipman, A. W. Merrison, and H. Paul, Nuovo Cimento 16, 490 (1960): $\tau_+ = 25.46 \pm 0.32$ nsec. H. L. Anderson, T. Fujii, R. H. Miller, and L. Tau, Phys. Rev. 119, 2050 (1960): $\tau_+ = 25.6 \pm 0.8$ nsec. M. Eckhause, R. J. Harris, Jr., W. B. Shuler, R. T. Siegel, and R. E. Welsh, Phys. Letters 19, 348 (1965): $\tau_+ = 26.01 \pm 0.02$ nsec. K. F. Kinsey, F. L. Lokkowicz, and M. E. Nordberg, Jr., University of Rochester Report No. UR-875-112, 1965 (unpublished): $\tau_+ = 26.40 \pm 0.08$ nsec.

ERRATA

SINGLE AND DOUBLE IONIZATION OF He BY ELECTRONS. M. H. Mittleman [Phys. Rev. Letters 16, 498 (1966)].

Subsequent to the publication of this Letter, Professor R. Novick pointed out a paper by W. E. Lamb, Jr., and Miriam Skinner [Phys. Rev. 78, 539 (1950)], "The Fine Structure of Singly Ionized Helium." The idea of calculating the ratio σ^{++}/σ^{+} by assuming that the relaxation process was the mechanism for the second ionization, which was the basis of my Letter, was used there in an appendix.

RELATIVISTIC CORRECTIONS FOR TERRESTRIAL CLOCK SYNCHRONIZATION, W. J. Cocke [Phys. Rev. Letters 16, 662 (1966)].

Change the sentence beginning in the second line of the second column on page 663, which reads "Drifts caused by the change in the solar ··· longer than a day," to read as follows:

"Of course, drifts caused by the change in the solar and lunar gravitational potentials across the earth's diameter cancel to first order because the earth as a whole is in free fall."