Precise Measurement of the K^+/K^- Lifetime Ratio*

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In this paper the details of a previously reported precise measurement of the K^+/K^- lifetime ratio are described. Using a separated beam at the Brookhaven AGS, we have counted the fraction of 1.6- and 2.0-GeV/c K mesons surviving at distances up to 2000 in. The result of the measurement yields $\tau(K^+)/\tau(K^-)-1=-0.00090\pm0.00078$, indicating no violation of the CPT theorem. No evidence for deviations from an exponential decay law or for the existence of long-lived K mesons was found. The upper limit for any long-lived K mesons in the beam is 3×10^{-3} at the 90% confidence level.

I. INTRODUCTION

Soon after the formulation of the CPT theorem[1] it was shown[2] that the total decay rate (lifetime) of a particle and its antiparticle must be equal to first order in the weak interactions. Equality of lifetimes would immediately follow if the decay Hamiltonian was invariant under C or CP; however, as is well known, both C and CP are violated in weak decays so that the observed equality is a consequence of the invariance of H_w under CPT.

The fact that the π^+/π^-, K^+/K^-, $\Lambda^0/\bar{\Lambda}^0$, etc., masses, lifetimes, etc. are approximately equal has been known for a long time[3]; the μ^+/μ^- lifetime ratio has been measured accurately[4] to be $\tau(\mu^+)/\tau(\mu^-)=1.000\pm0.001$. Earlier measurements of $\tau(K^+)/\tau(K^-)$ were at the 10% level.[5] The recent discovery of CP violation in weak decays[6] motivated an experimental search for other violations of invariance in weak decays. Two groups have recently measured the π^+/π^- lifetime ratio with the corresponding results:

(a) $\tau(\pi^+)/\tau(\pi^-)-1=+0.004\pm0.007$ (Bardon *et al.*[7]),

(b) $\tau(\pi^+)/\tau(\pi^-)-1=+0.00064\pm0.00067$ (Ayres *et al.*[8]).

We measured the K^+/K^- and π^+/π^- lifetime ratios to find[9]

$$\tau(K^+)/\tau(K^-)-1=-0.00090\pm0.00078,$$
$$\tau(\pi^+)/\tau(\pi^-)-1=+0.0040\pm0.0018.$$

Another recent measurement of the partial decay rate for $K^\pm\to\mu^\pm+\nu$ confirms these results by obtaining[10]

$$(K^+\to\mu^+\nu)/(K^-\to\mu^-\nu)-1=-0.0054\pm0.0041.$$

Also,

$$(K^+\to\pi^+\pi^+\pi^-)/(K^-\to\pi^-\pi^-\pi^+)-1=-0.0004\pm0.0021.$$

It is therefore clear that to these accuracies no violation of CPT has been observed. The purpose of this paper is to describe in detail the experimental method used in our measurement of K^+/K^- lifetime ratio reported previously[9]; the π^+/π^- measurement was incidental to the K^+/K^- experiment and therefore did not achieve the same accuracy.

We begin with a general discussion on lifetime measurement techniques, and next the apparatus is described. In Sec. IV, the data are presented and the analysis procedure followed in detail.

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† During the performance of this experiment these authors held guest appointments at Brookhaven National Laboratory.

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II. APPROACHES TO LIFETIME RATIO MEASUREMENTS

Perhaps the most traditional way for measuring a lifetime is to count, as a function of time, the decay products emitted from a sample of particles which are at rest. While this approach can be used for positive mesons, it is inadequate in the case of negatively charged ones; this is due to the fact that slow negative mesons are attracted by the positive nuclei of the surrounding matter and undergo nuclear interactions. The rate for these interactions is usually much faster than the decay so that it almost completely masks it.[11] Thus, we must measure the K^- lifetime in flight.

Since we are interested in a possible relative difference of two equal lifetimes, we must measure both K^+ and K^- under identical conditions. Any differences in the nuclear properties or beam characteristics of the K^+ versus K^- may introduce spurious systematic errors in the lifetime ratio and must be carefully taken into consideration.

Since the measurement has to be made in flight, the observed lifetime in the laboratory must be transformed to the rest frame of the meson. Thus, an exact knowledge of the momentum is essential; this, coupled with the knowledge of the decay length, is equivalent to the precise timing required in an experiment at rest. However, the relativistic time dilation, depending on the momentum chosen, imposes a necessity for long decay paths.

One may elect to measure the decay products of the meson for a given length of path or one may measure the number of mesons that survive after traversal of a given distance. In the former case, one is usually restricted in path length, and a very accurate knowledge of the collection solid angle is needed. In the latter case, a well-collimated beam is required so that particles are lost only due to decay; it is also needed to discriminate against decay products that remain in the beam. We have used the second technique, and for that case a simple calculation shows that the error in lifetime due to statistics is

$$\frac{\Delta\tau}{\tau}=\frac{\Delta R}{R}\left(\frac{cp\tau}{lm}\right)=\frac{1}{\sqrt{N_0}}\left(\frac{N_0-N}{N}\right)^{1/2}\left(\frac{lm}{cp\tau}\right)^{-1}, \qquad (1)$$

where $R=N/N_0=e^{-lm/cp\tau}$ is the attenuation ratio, N_0 is the number of mesons traversing position s_0, N is the number of mesons not having decayed when traversing position s, $l=s-s_0$ is the length of the decay path, m is the mass of the meson, p is the momentum of the meson, and c is the speed of light. The quantity $lm/cp\tau=t/\gamma\tau$ is simply the number of proper lifetimes traversed by the meson. If the error is only statistical, then for fixed N_0 Eq. (1) has a minimum at $lm/cp\tau=1.59$. If, however, one is not limited by incident flux, it is preferable to move to larger distances, since the factor $(lm/cp\tau)^{-1}$ in Eq. (1) reduces all errors correspondingly. On the other hand, errors in the decay path, momentum, or mass of the K meson affect the measured lifetime linearly.

In this experiment we are mainly interested in the relative ratio of the two lifetimes, so that the errors in mass and decay length cancel out of the ratio. Similarly the correction for decay products (counted as surviving particles) appears in the ratio only as a second-order effect.[12] The most serious sources of systematic errors can be listed as follows:

(a) differences in composition and phase-space properties of positive and negative beams;
(b) difference in nuclear interaction of positive and negative particles in the detector;
(c) differences in relative momentum.

To compensate for these effects we have taken the following precautions:

(a) An electrostatically separated beam was used so that the main fraction of protons was eliminated from the positive beam, and the K/π ratio was improved by a factor of 50. The focusing of the beams was checked by measuring the transmission of stable particles; protons in one case and antiprotons in the other.

(b) The flight path was in vacuum and the detector material in the path was reduced to a minimal value. Initially at s_0 the K mesons have to be positively identified by means of Čerenkov counters. Two counters were required to obtain a sufficient rejection of unwanted particles. Placing these Čerenkov counters at s_0 introduces of the order of 2 g/cm^2 of material in the beam; to avoid this effect we redefined the initial beam intensity N_0 by means of a very thin and small ($\frac{1}{32}$ in. thick, $\frac{1}{2}$ in. diam) scintillator some distance downstream of the Čerenkov counters. To count the survivors at s, we would prefer to again positively identify them as K mesons; however, assuming long flight paths, efficiency of the measurement is much more important than rejection of decay products. We therefore used only scintillation counters for the actual measurement. An additional Čerenkov counter at s was used as a check only.

(c) We made very careful momentum measurements which ensured relative accuracy to better than 0.1%. Furthermore, frequent (16) alternations of the beam polarity were made in order to randomize such momentum setting errors. Measurements in this experiment were made at momenta of 1.6 and 2.0 GeV/c.

[11] An exception to this statement is the capture of negative muons in pure hydrogen where the formation of muonic molecules delays the capture of the muons which proceeds with a rate of $\Gamma=469\pm42$ sec^{-1}. See J. E. Rothberg *et al.*, Phys. Rev. **132**, 2664 (1963).

[12] The correction for decay products is of the order of 0.75%/in. of counter diameter. Thus, even if the K^+ and K^- lifetimes differed by 1%, the systematic asymmetry introduced by this correction would be less than 3×10^{-4}.

III. EXPERIMENTAL APPARATUS

A schematic layout of the experiment is shown in Figs. 1(a) and 1(b). The 10° beam from the G-10 target of the Brookhaven AGS was used (separated beam 5).[13] The K-decay flight path originated at the triple focus of this beam and extended for approximately 2000 in. with provisions for placing a detector system at 700, 1400, or 2000 in. away from the triple focus.

Separation is produced in two electrostatic separators labeled BS No. 1 and BS No. 2 on this diagram; these were operated at 380 and 400 kV, respectively, with a 4-in. plate separation to give a pion image at the mass slit displaced about 0.340 in. from the K image at 1.0 GeV/c and 0.200 in. at 2.0 GeV/c. The nominal momentum acceptance for this experiment was $\pm 0.5\%$ and was determined by two blocks offset by ± 16 in. with respect to the central momentum focus in order to give a sharp cutoff to the momentum acceptance. Experimental measurement of the shape of the momentum spectrum indicates an actual momentum spread of about $\pm 0.75\%$; the additional spread may have been due to scattering at various places in the beam, particularly at the mass slit and momentum slit. The purpose of the sextupole was to give an improved image of the off-momentum particles at the mass slit. It was found that for the small momentum acceptance of this experiment, operation of the sextupole did not give an improved K to π ratio, and therefore the sextupole was not used. The mass slit consists of two tapered blocks of Hevimet and the separation at the narrowest point for this experiment was 0.205 in. A counter telescope consisting of two long thin scintillators, the narrowest of them $\frac{1}{4}$ in. high, was placed in front of the mass slit mounted on a remote worm-gear drive. This arrangement was found useful in focusing the beam on the slit. The second bending magnet together with the three quadrupoles in front of it have the effect of recombining the off-momentum rays so that there is zero momentum dispersion at the triple focus for the axial rays. There is, however, some chromatic aberration at this point, so that the theoretical image width at this point was 0.430 by 0.400 in. for the $\frac{1}{2}\%$ momentum acceptance used in this experiment.

A diagram of the extension of the beam past the

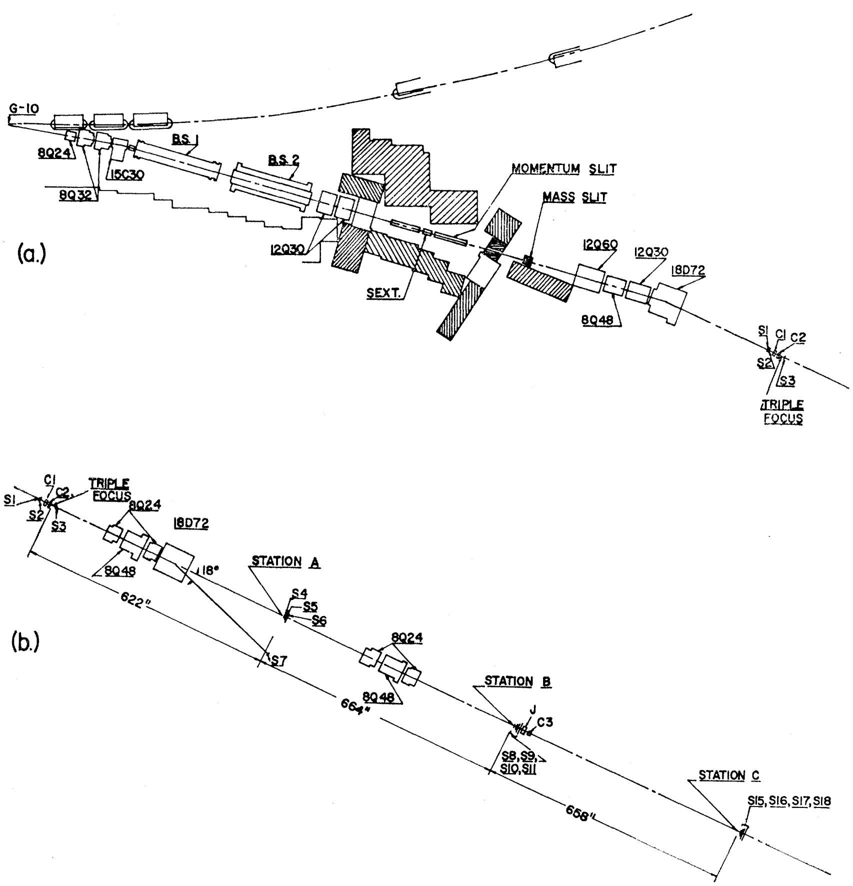

FIG. 1. Arrangement of the beam. (a) The primary beam from the AGS G-10 target to the triple focus. (b) The secondary beam from the triple focus to the three measuring stations A, B, or C.

[13] We operated this beam quite close to its original design parameters. We are indebted to B. Barish for making his data on this beam available to us.

triple focus is shown in Fig. 1(b). The three quadrupoles 8Q24, 8Q38, and 8Q24 form an image at station A of the triple focus; the second quadrupole triplet forms an image of station A either at stations B or C. The first quadrupole triplet was placed as close as possible, consistent with reasonable magnification, to the triple focus so as to catch Coulomb-scattered particles from the counters at this point. Theoretically, any particle that gets through these first three quadrupoles should stay within the apertures of the rest of the beam. The 18D72 magnet D_3, normally off, was used to measure the momentum spectrum of the beam. This magnet deflects the beam about 18° onto a thin vertical counter S_7. This counter was $\frac{1}{8}$ in. wide and mounted on a remotely operated precision worm-gear drive so that by moving the counter through the deflected beam a horizontal beam profile could be obtained. The field in D_3, used to measure the beam momentum, was monitored by a NMR probe. All other fields in the beam were determined by current shunts; in addition there were Hall probes in all bending magnets and during part of the experiment a second magnetic resonance probe was used in D_2, and 18D72 in front of the triple focus.[14]

In Fig. 2, we show the theoretically calculated phase space of the beam (a) at the triple focus and (b) at station A for a target size of ± 0.020 in. and ± 20-mrad divergence.

The counter system at the triple focus is shown in Fig. 3(a). Counters S_1, S_2, S_{3A}, and S_3 are plastic scintillators defining the beam; their dimensions are given in Table I. Counters C_1 and C_2 are differential

TABLE I. Dimensions and positions of all scintillation counters used in this experiment (in inches).

	Diameter	Thickness	Distance from origin	Comments
S_1	0.5	$\frac{1}{8}$	−41.0	Beam defining
S_2	1	$\frac{1}{8}$	−40.5	
S_{3A}	0.5	$\frac{1}{8}$	−20.0	
S_3	0.5	$\frac{1}{32}$	0	
S_4	1.5	$\frac{1}{8}$	622.0	Station A
S_5	2.0	$\frac{1}{8}$	622.6	
S_6	2.5	$\frac{1}{8}$	623.3	
S_7[a]	$\frac{1}{8}\times 4$[b]	$\frac{1}{4}$		Momentum measuring
S_8	1.5	$\frac{1}{8}$	1285.7	Station B
S_9	2.0	$\frac{1}{8}$	1286.3	
S_{10}	2.5	$\frac{1}{8}$	1287.7	
S_{16}[a]	3	$\frac{1}{4}$	1942.9	Station C
S_{17}[a]	4	$\frac{1}{4}$	1943.9	
S_{18}[a]	5	$\frac{1}{4}$	1945.4	

[a] Provided with Lucite light pipes; all other counters had air light pipes.
[b] Rectangular counter 4 in. high.

[14] The first bending magnet was a 15C30 magnet and it was not possible to find an accessible region of sufficient homogeneity for operation of a magnetic resonance probe.

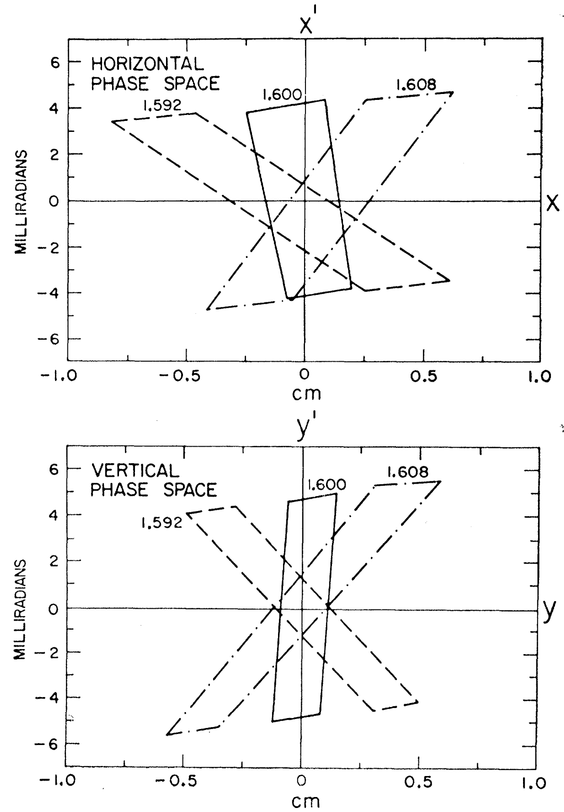

FIG. 2. Theoretically calculated phase space for a ± 0.020-in. target and a ± 20-mrad divergence at the triple focus.

Čerenkov counters[15] with liquid radiators, used to identify K mesons. The radiator cells were $\frac{1}{2}$ in. thick and could be easily changed to accept different momenta or a different particle. Typical efficiences for 1.6-GeV/c K mesons were 70% (as measured by one

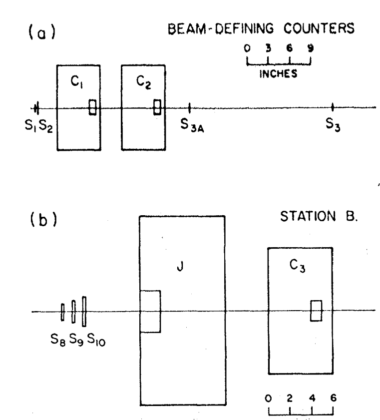

FIG. 3. Arrangement of the counters, (a) at the triple focus, and (b) at a typical downstream station, here station B.

[15] S. Ozaki, J. J. Russell, E. J. Sacharidis, L. C. L. Yuan, and J. T. Reed, Nucl. Instr. Methods 35, 301 (1965). Our counters, however, did not have the anticoincidence ring feature.

counter monitoring the other). Typical rejection of π mesons, per counter, was $\sim 10^{-4}$, so that a combined rejection significantly better than 10^{-5} was achieved[16]; this was measured by tuning the separators for pions.

Typical fluxes of 500–2000 K mesons per AGS pulse were used. At 1.6 GeV/c the beam composition was typically $K^+/\pi^+ \sim \frac{1}{3}$ and $K^-/\pi^- \sim \frac{1}{7}$, and the maximum attenuation of the K beam (by decay) was 20. Consequently, even at the farthest station, the K count has a purity better than 10^3. Indeed, the limit on this number arises from accidental coincidences between the counts in the downstream scintillators and the Čerenkov counters. This was continuously monitored and was kept[17] below 10^{-3}.

The beam-defining counters S_1, S_2, S_{3A}, and S_3, all had air light pipes as did all scintillation counters in this experiment, so as to eliminate the possibility of spurious counts from Čerenkov light in the light pipes. S_3 was made as thin as possible (0.032 in.) so as to reduce the amount of multiple scattering and nuclear interaction that must be corrected for in this counter; products of interactions in the counters upstream of S_3 do not, in general, hit S_3, so they do not need to be corrected for. The geometry of S_{3A} and S_3 is such that, in theory, any particle going through these two counters should be collected in the quadrupole telescope. The triple focus was placed somewhere between S_3 and S_{3A}. In practice, the last three quadrupoles were tuned so as to maximize the counting rate.

A typical back counting station, in this case station B, is shown in Fig. 3(b). There are three scintillation counters S_8, S_9, and S_{10} with diameters 1.5, 2, and 2.5 in., respectively. These are in the form of round disks $\frac{1}{8}$ in. thick with a common axis. The purpose of this arrangement is threefold: (a) The existence of several counters provides parallel channels which immediately reflect instrumental deficiencies and/or variations in system performance. Small deviations in beam position or focusing manifest themselves first in the smallest counter (S_8), whereas the larger counters are still unaffected. (b) It was possible to tune the beam onto the smallest counter with much better sensitivity than onto a larger one; yet we are assured of optimum focusing onto the following larger counters as well. (c) The larger counters collect proportionally more decay products; thus an extrapolation to zero diameter is possible. This extrapolation was consistent with the theoretically calculated (Monte Carlo) correction for decay products.[12] Finally, the efficiency of these scintillators was monitored continuously by a smaller counter placed behind them. For all data accepted, this efficiency was >0.999. The dimensions and positions of all counters are given in Table I.

Another important feature of our apparatus was the possibility of testing experimentally the collection efficiency of our detector for stable particles (what we call the transmission). This was done by tuning *only the separators* to protons (antiprotons) while the rest of the beam transport and detectors remained identical. Such a measurement must yield 1.000 after all corrections have been applied and, if slightly different from unity, can be used to renormalize the K data. Deviations of the transmission from unity we attribute to (a) Coulomb scattering in S_3, (b) nuclear interactions in S_3, (c) nuclear interactions in the vacuum-pipe Mylar windows and residual gas, (d) dead-time losses in the scalers and circuitry, (e) misalignment of the beam with respect to its theoretical axis, and finally (f) aberrations in focusing quadrupoles.

Of these effects, (a), (b), and (c) are the most serious ones; in particular, (b) and (c) are asymmetric between K^+ and K^- mesons caused by the difference in the

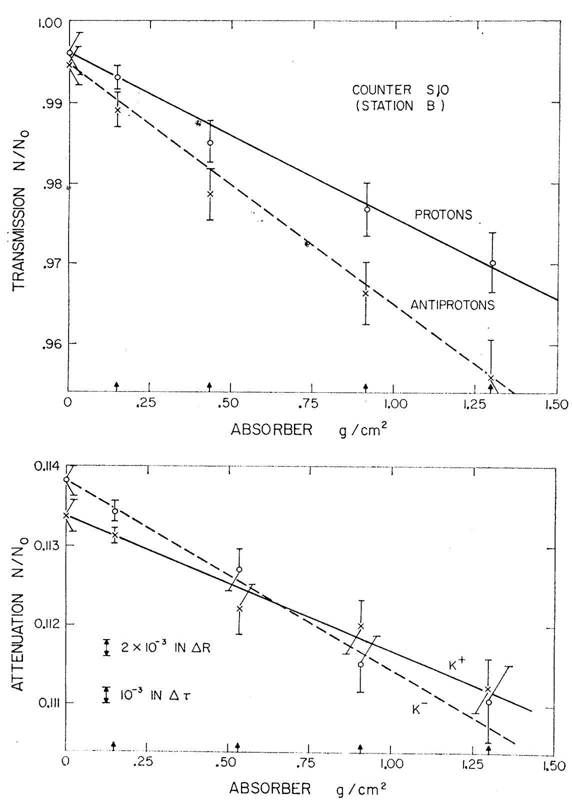

FIG. 4. (Top) Typical fit to the transmission data as a function of absorber thickness for p and $\bar{p}$. The extrapolated values to zero material are shown. (Bottom) Typical fit to the attenuation data of one run. Also indicated is the sensitivity of the ratio R and the lifetime τ to the data.

[16] The combined rejection when two such counters are operated in coincidence is found to be highly correlated, mainly caused by the production of knock-on electrons. Nevertheless, the combined rejection was of the order of 10^6.

[17] Considering an instantaneous rate of 2000 counts/sec and our time resolution of 10^{-8} sec, we have an accidental rate of 2×10^{-5}. At worst the ratio of K mesons/pions at the *downstream* counters was 200, so that the accidental contribution was at most 10^{-3} of the surviving K-meson count.

TABLE II. Effect of material placed in the path of the beam. We give the fractional change in "transmission" and "attenuation" when 1 g/cm² of Lucite is placed immediately downstream of S_3. The errors are typically 2 to 5% of the quoted number for the transmission and 20 to 30% for the attenuation.

	Counter	Transmission p	Transmission $\bar{p}$	Attenuation K^+	Attenuation K^-
Incident momentum 1.6 GeV/c					
Measured fractional change in	S_4	0.025	0.047	0.021	0.031
	S_5	0.019	0.036	0.016	0.023
	S_6	0.019	0.034	0.015	0.022
	S_8	0.021	0.037	0.020	0.024
	S_9	0.019	0.033	0.016	0.020
	S_{10}	0.019	0.033	0.017	0.021
Calculated fractional change for CH_2		0.019	0.033	0.009	0.011
Cross sections used for calculation	$\sigma_T(H_2)$	48	100	18.0	32.0
(mb/nucleon)	$\sigma_T(C)$	30	50	13.8	18.5
Incident momentum 2.0 GeV/c					
Measured fractional change in	S_4	0.021	0.032	0.012	0.016
	S_5	0.019	0.030	0.010	0.014
	S_6	0.018	0.030	0.010	0.014
	S_8	0.022	0.031	···	0.032
	S_9	0.020	0.031	0.015	0.021
	S_{10}	0.020	0.030	0.014	0.020
	S_{16}	0.031	0.040	0.033	0.025
	S_{17}	0.022	0.034	0.023	0.017
	S_{18}	0.020	0.030	0.018	0.008
Calculated fractional change for CH_2		0.020	0.030	0.009	0.011
Cross sections used (mb/nucleon)	$\sigma_T(H_2)$	47	90	17.5	29.0
	$\sigma_T(C)$	32	45	12.0	16.0

TABLE III. Measured transmissions of protons (+) and antiprotons (−) extrapolated to zero material. These values were used to renormalize the K-attenuation data. For the raw transmissions see Fig. 4 and Table III.

Run and polarity	Nominal momentum (GeV/c)	Station	Counter and corresponding extrapolated transmission {error increased by $[\chi^2/(n-2)]^{1/2}$ (when necessary)}		
1+	1.6	A	S_4 0.997477±0.000367	S_5 0.997613±0.000166	S_6 0.996560±0.000203
1−	1.6	A	S_4 0.997359±0.001082	S_5 0.996873±0.000461	S_6 0.995310±0.000392
2+	1.6	A	S_4 0.997694±0.000327	S_5 0.997402±0.000342	S_6 0.996307±0.000360
2−	1.6	A	S_4 0.998560±0.000709	S_5 0.996250±0.000700	S_6 0.994700±0.000740
3+	1.6	B	S_8 0.996285±0.000345	S_9 0.996785±0.000212	S_{10} 0.996123±0.000310
3−	1.6	B	S_8 0.995024±0.000516	S_9 0.994700±0.000466	S_{10} 0.995687±0.000191
4+	1.6	B	S_8 0.996204±0.000177	S_9 0.997222±0.000158	S_{10} 0.996768±0.000149
4−	1.6	B	S_8 0.993531±0.000532	S_9 0.996811±0.000302	S_{10} 0.995372±0.000307
5+	2.0	A	S_4 0.995944±0.000242	S_5 0.994525±0.000239	S_6 0.994302±0.000201
5−	2.0	A	S_4 0.993260±0.000325	S_5 0.993689±0.000260	S_6 0.992733±0.000274
6+	2.0	B	S_8 0.985291±0.000575	S_9 0.995891±0.000337	S_{10} 0.995873±0.000513
6−	2.0	B	S_8 0.982086±0.000443	S_9 0.995366±0.000237	S_{10} 0.994321±0.000248
7+	2.0	B	S_8 0.980284±0.000541	S_9 0.996610±0.000155	S_{10} 0.996387±0.000151
7−	2.0	B	S_8 0.994994±0.000282	S_9 0.995903±0.000286	S_{10} 0.994797±0.000323
8+	2.0	C	S_{16} 0.986948±0.000485	S_{17} 0.992973±0.000235	S_{18} 0.987384±0.000321
8−	2.0	C	S_{16} 0.987324±0.000863	S_{17} 0.992568±0.000243	S_{18} 0.983116±0.000272

nuclear interaction cross section.[18] To account for such losses, we have measured them experimentally by placing additional material immediately downstream of S_3. The transmission as a function of material thickness is shown in Fig. 4 for typical p, $\bar{p}$, K^+, and K^- runs. The thickness of S_3 was 0.151 g/cm², and when we extrapolate to zero thickness we obtain the corrected transmission of the system. The slopes of the data on Fig. 4 are consistent with the known interaction of K^+ and K^- mesons in CH_2, as given in Table II.

We have also placed additional material in other parts of the beam, in particular upstream of S_3 at the position of S_1, S_2, and of the Čerenkov counters. We found that this had no effect on the transmissions, confirming our view that particles interacting upstream miss S_3.

These two auxiliary measurements, proton transmission and attenuation due to material, were considered so essential to the reliability of the experiment that they were made before and after every kaon attenuation measurement. In Table III are given the final extrap-

[18] Whereas the K^-p total cross section is almost twice as large as the K^+p cross section, the K^- and K^+ cross sections on carbon differ much less (see Table III). For the 1.6-GeV/c data, the total amount of material was 0.242 g/cm².

olated transmissions T' as measured and used in this experiment.

Shown also in Fig. 3(b) is a differential Čerenkov counter (J), similar to the C counters but with a larger aperture (radiator diameter 4 in. instead of 2 in.). Counter J was used in stations B and C as an additional way of determining the kaon attenuation. This method is free of decay product and accidental correction. On the other hand, it is dependent on the stability of the efficiency of J for K^+ and K^- mesons. The absolute efficiency of J was monitored by a fourth Čerenkov counter C_3 (2-in.-diam radiator) and was of the order of 0.98; the rejection of J was of the order of 0.02. The results obtained by this method were less accurate than with the scintillation counters and were used mainly as a checking procedure.

Finally, a momentum measurement (as explained previously) was also made before each beam alternation. A typical result is shown in Fig. 5; clearly the resolution in the measurement of the momentum spectrum permits relative measurements of the mean momentum to better than $1/10^3$. To exhibit this we shifted the primary beam magnets by 0.13%; the measurement of the spectrum then yielded the dashed curve which is shifted by the expected amount.

The entire decay path was always in vacuum. When measurements were performed at stations B or C the detectors of the upstream stations A (or A and B) were removed from the beam line and the vacuum path restored. The detectors were mounted on prevision worm-gears so that it was possible to reposition them with an accuracy of $\frac{1}{32}$ in.

IV. ANALYSIS OF DATA

As mentioned before, data were taken for various decay path lengths, namely, at stations A, B, and C. Of the order of 10^7 incident K mesons were counted for each measurement. For set of data, the attenuation of K mesons was measured with zero material as well as

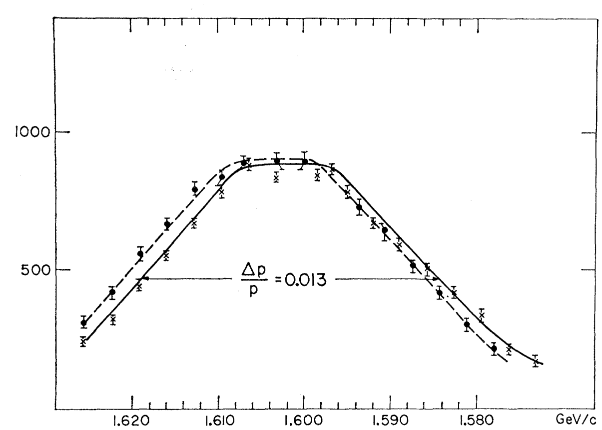

FIG. 5. Typical momentum spectrum at 1.6 GeV/c as taken by dispersing the beam in D_3. The dashed curve is obtained by shifting the primary beam momentum setting by 0.002 GeV/c.

with added material downstream of S_3, in order to permit extrapolation to zero thickness. Similarly, transmission measurements with zero and added material were made, as well as momentum measurements. Furthermore, each set of data was broken into several subruns of the order of 0.5 to 1×10^6 K mesons.

All data were punched in IBM cards to allow a systematic statistical analysis. The internal consistency of each set was examined and subsets with deviations from the mean larger than three standard deviations were rejected: this resulted in eliminating less than 5% of the total data. In any event, inclusion of these data does not alter the final result, and in Table V we give data with and without these exclusions.

At first, all K-attenuation measurements were referred to the nominal momentum, 1.6 or 2.0 GeV/c. This was done by using for the K mean life 12.24×10^{-9} sec and the difference between the nominal and the measured exact momentum; since the difference from the nominal momentum was typically a few parts in 10^3 and never exceeded 4×10^{-3}, any error possibly introduced in the attenuation by this procedure is well below 10^{-4}.

Next, all K-attenuation data of the same run were combined for each counter S_i of each station. This was done by performing a linear least-squares fit as a function of added absorber material (downstream of S_3) and extrapolated to zero (S_3 thickness). The statistical error of each subset was propagated through the least squares to give the over-all error of the fit. If the χ^2 for the fit was larger than $n-2$ (where n is the number of subsets used in the fit) the over-all error was increased by a factor of $[\chi^2/(n-2)]^{1/2}$. As a result, we obtain an "extrapolated attenuation" R' for each counter S_i of each station for each run.

The next step was to treat, for each run, the transmission data in an exactly similar fashion. As a result, we obtain an "extrapolated transmission" T' for each counter S_i of each station for each run (see Table III). Finally, using only data for which $T'>0.99$, we renormalized R' so that $R''=R'/T'$ is the "normalized attenuation" for each counter S_i of each station for each run. Here by run we refer to the entire data taken at one station between two alternations of the beam polarity; a total of 16 runs were used, 8 at each polarity. Runs for the same momentum and station were combined. In Table IV are given the nominal momenta, total flux, stations, counters, and respective normalized attenuation that yielded usable information for these 10 combined runs; namely, a total of 30 attenuations, since for each run three counters register. Rejection of inconsistent data (which was traced to minor equipment malfunctions) or data with poor transmission leaves 29 attenuations. It is clear that the three attenuations from the same run are completely correlated as far as the statistics are concerned, and would be equal except for the decay product correction

TABLE IV. Normalized attenuations R'' for K mesons and their errors. These data are used directly for determining the lifetime ratio.

Run and polarity	Nominal momentum (GeV/c)	Incident K's in 10^6	Station	Counter and normalized attenuation R'' {error increased by $[\chi^2/(n-2)]^{1/2}$ (when necessary)}		
1, 2+	1.6	3.5	A	S_4 0.266693±0.000422	S_5 0.267478±0.000419	S_6 0.268199±0.000421
1, 2−	1.6	2.4	A	S_4 0.266647±0.001271	S_5 0.267398±0.000960	S_6 0.268197±0.000974
3, 4+	1.6	5.2	B	S_8 0.064632±0.000362	S_9 0.065560±0.000226	S_{10} 0.065930±0.000177
3, 4−	1.6	5.7	B	S_8 0.064714±0.000298	S_9 0.065715±0.000227	S_{10} 0.066088±0.000176
5+	2.0	3.8	A	S_4 0.347024±0.000383	S_5 0.348365±0.000384	S_6 0.349207±0.000383
5−	2.0	3.4	A	S_4 0.347741±0.000384	S_5 0.348389±0.000379	S_6 0.349290±0.000381
6, 7+	2.0	9.6	B	S_8 Reject	S_9 0.113368±0.000196	S_{10} 0.113776±0.000200
6, 7−	2.0	8.8	B	S_8 0.111847±0.000740	S_9 0.113809±0.000203	S_{10} 0.114237±0.000213
8+	2.0	6.2	C	S_{16} 0.038100±0.000276	S_{17} 0.038119±0.000192	S_{18} 0.038989±0.000218
8−	2.0	6.2	C	S_{16} 0.038135±0.000265	S_{17} 0.038396±0.000189	S_{18} 0.039260±0.000202

which increases linearly[19] with counter diameter. The 29 normalized attenuations as given in Table IV are the basic data from which a comparison of the lifetimes, or the absolute values will be obtained. They are presented in such detail because we believe that their internal consistency is the best measure of all but the systematic errors of our experiment.

We have then formed the ratio of the attenuations for each momentum and for each counter. This, in turn, yields the ratio of K^+/K^- lifetime implied from each pair of such measurements, since

$$\tau_+/\tau_- - 1 = (lm/cp\tau)^{-1}(R_+R_-/-1)\,. \qquad (2)$$

The results are shown in Table V both for the selected and unselected data, with their respective errors.

Since the ratios obtained from the three counters of the same stations are statistically completely correlated, they must be equal and we have, therefore, chosen to form their arithmetic mean. This results in five final independent determinations of the lifetime ratio which are given in column 5 of Table V.

Systematic effects: So far only statistical and random errors have been taken into account. We have examined the possibility of the presence of systematic errors that would appear differently for positive versus negative particles. We believe that the effects of the nuclear interaction have been properly accounted for by our extrapolation procedure. Similarly, we believe that the beam properties and composition as well as the accidental rates are sufficiently identical to preclude systematic effects. The only source of systematics that we have found and taken "into consideration" is the effect of the earth's field. This was measured to have in our experimental area a vertical component of 0.40 G.[20] Whereas the presence of the earth's field affects the entire beam, we believe that the transmission measurements take account of such differences. However, the presence of the field directly affects the measurement of the momentum that we perform when deflecting the beam in D_3. For our configuration the ratio of the beam shift due to the earth is 0.0002 of that due to the magnet at 1.6 GeV/c so that for the same field in D_3 and the same average beam deflection, the true momentum of positive particles is less by 0.0004 then that for the corresponding negative particles.[21]

Consequently, the lifetime ratios of column 5 Table V are given in the last column (6) after the application of this 0.0004 correction.

A. Lifetime Ratios

We are now prepared to obtain the final value for the ratio of the K^+ and K^- lifetimes, starting from the five corrected ratios of column 6 Table V. We may average these ratios weighted as $1/\sigma^2$ to obtain

$$\tau_+/\tau_- - 1 = -0.00090 \pm 0.00078\,, \qquad (3)$$

with $\chi^2 = 0.600$ for four degrees of freedom. We believe that this number contains the maximum information. The error quoted here, as well as in Eq. (4), is 1 standard deviation, and contains no systematic effects, except for the increase of the propagated statistical error when so indicated by a poor χ^2 fit.

The above method of averaging obviously emphasizes the results with the smallest statistical error, namely the 2.0-GeV/c data at stations A and B. If, on the other hand, one wishes to take full advantage of the repeated beam polarity alternations (in order to randomize the errors in relative momentum setting) it is perferable to perform an average of the five ratios but with equal weight for each. In this way, we obtain

$$\tau_+/\tau_- - 1 = -0.00049 \pm 0.00097\,, \qquad (4)$$

with $\chi^2 = 12.18$ for 13 degrees of freedom (d.f.). This number contains *less* information than the one given in Eq. (3), as reflected by the larger uncertainty; however, it can be taken as the upper limit of a possible

[19] At first thought one would expect that the decay products would depend on the area of the counter. Consider, however, an average decay angle θ; it is clear that the decay products counted are proportional to the path length l of the K meson for which a decay product emitted at θ still reaches the counter. This is simply $l = R/\tan\theta$. For different momenta $\tan\theta$ is proportional to $1/p$. However, the number of decays per unit length is also proportional to $1/p$ and thus the decay product correction is also nearly energy-independent.

[20] The stray AGS field and other stray fields from current conductors were measured $\lesssim 0.05$ G. Note that the earth field acts over a much larger distance than the size of the bending magnet D_3.

[21] Our magnetic analysis system bends to the right (clockwise).

TABLE V. Lifetime ratios ($\tau_+/\tau_- - 1$) in units of 10^{-3} resulting from the data in Table IV. The ratios are calculated for (1) all data, (2) data selected for internal consistency (95% of all data), (3) no extrapolation performed to correct for finite thickness of counter S_3, and (4) data not corrected for variations in transmission of the beam transport system.

	$p\pm1.6$ GeV/c; station A; $l=622$ in.; $lm/cp\tau=1.34$; 5.9×10^6 kaons; statistical error ±1.5				
Data	S_4 (1.5 in.)	S_5 (2 in.)	S_6 (2.5 in.)	Mean	Mean corrected for earth's field
1. All	$+0.32\pm2.9$	-0.31 ± 3.7	-0.28 ± 4.6		
2. Selected	$+0.13\pm3.8$	$+0.23\pm3.0$	$+0.01\pm3.0$	$+0.12\pm3.0$	$+0.51\pm3.3$
3. No extrapolation	$+2.04\pm3.1$	-2.63 ± 3.2	-4.12 ± 3.5		
4. No transmission	-1.91 ± 3.1	-3.72 ± 1.9	-4.45 ± 1.9		
	$p=1.6$ GeV/c; station B; $l=1286$ in.; $lm/cp\tau=2.73$; 10.9×10^6 kaons; statistical error ±1.3				
Data	S_8 (1.5 in.)	S_9 (2 in.)	S_{10} (2.5 in.)	Mean	Mean corrected for earth's field
1. All	-0.35 ± 2.5	$+2.49\pm5.2$	-0.64 ± 1.4		
2. Selected	-0.47 ± 2.7	-0.86 ± 1.8	-0.88 ± 1.4	-0.74 ± 2.0	-0.35 ± 2.0
3. No extrapolation	-0.09 ± 4.2	-0.47 ± 2.4	-0.12 ± 2.1		
4. No transmission	$+0.29\pm2.8$	-0.71 ± 1.8	-0.50 ± 1.4		
	$p=2.0$ GeV/c; station A; $l=622$ in.; $lm/cp\tau=1.06$; 7.2×10^6 kaons; statistical error ±1.5				
Data	S_4 (1.5 in.)	S_5 (2 in.)	S_6 (2.5 in.)	Mean	Mean corrected for earth's field
1. All	-2.24 ± 1.5	-0.16 ± 1.5	-0.31 ± 1.5		
2. Selected	-1.95 ± 1.5	-0.06 ± 1.5	-0.23 ± 1.5	-0.75 ± 1.5	-0.44 ± 1.5
3. No extrapolation	-1.31 ± 2.0	$+0.73\pm1.9$	$+0.64\pm1.5$		
4. No transmission	$+0.59\pm1.4$	$+0.73\pm1.4$	$+1.26\pm1.4$		
	$p=2.0$ GeV/c; station B; $l=1286$ in.; $lm/cp\tau=2.16$; 18.4×10^6 kaons; statistical error ±0.9				
Data	S_8 (1.5 in.)	S_9 (2 in.)	S_{10} (2.5 in.)	Mean	Mean corrected for earth's field
1. All		-1.38 ± 1.1	-1.42 ± 1.1		
2. Selected		-1.77 ± 1.1	-1.84 ± 1.2	-1.81 ± 1.2	-1.50 ± 1.2
3. No extrapolation		-1.20 ± 1.7	-1.24 ± 1.7		
4. No transmission		-1.40 ± 1.2	-1.06 ± 1.2		
	$p=2.0$ GeV/c; station C; $l=1944$ in.; $lm/cp\tau=3.26$; 12.4×10^6 kaons; statistical error ±1.2				
Data	S_{16} (3 in.)	S_{17} (4 in.)	S_{18} (5 in.)	Mean	Mean corrected for earth's field
1. All	$+0.54\pm3.2$	$+0.69\pm2.2$	-2.92 ± 2.1		
2. Selected	$+0.27\pm3.0$	-2.19 ± 2.1	-2.10 ± 2.3	-1.34 ± 2.5	-1.03 ± 2.5
3. No extrapolation	$+1.34\pm4.2$	-1.48 ± 2.7	-1.70 ± 2.6		
4. No transmission	$+0.01\pm4.0$	-2.59 ± 2.6	-2.26 ± 3.0		

deviation of the lifetime ratio from unity as obtained by this experiment.

B. Absolute Lifetime

In order to obtain the absolute lifetime, it is first necessary to correct the attenuations for the number of decay products that are counted by the scintillation counters at the downstream end stations. We have performed a Monte Carlo calculation of this effect assuming a beam 1 in. in diameter but monochromatic and centered on the axis of the detection system. The contributions of the various decay modes at 1.6 GeV/c are given in Table VI and are also shown in Fig. 6; they vary linearly with counter diameter in agreement with the theoretical prediction. We find that the total correction is $(0.75\pm0.05)\%$ per inch of counter diameter nearly independent of the beam momentum. The experimentally observed effect was typically (at 1.6 GeV/c) 0.0059 ± 0.0010/in. diam after taking into account the small difference in path length (approximately $\frac{3}{4}$ in.) between successive counters.[22]

In Table VII we give the attenuations averaged over polarities, corrected for decay products and referred to the first counter of each station. Fitting these data to the form

$$-1/\ln R=\frac{c}{m}\frac{p}{l}\tau \tag{5}$$

gives the following value for the K^- mean life:

$$12.272\pm0.005 \text{ nsec}, \tag{6}$$

[22] There is also a small correction in the case of K^- mesons for charge-exchange interactions in the preceding counters. This is of the order of 2×10^{-4} or less.

TABLE VI. Results of a Monte Carlo calculation for the cn-o tributions to the decay product corrections at 1.6 GeV/c (in percent).

Decay and contribution	Counter diameter (in.) 0.5	1.5	2.5	3.5
$\mu^+\nu$ (63.2%)	0.18	0.56	0.95	1.33
$\pi^+\pi^0$(21.3%)	0.07	0.21	0.35	0.50
$3(\pi^+\pi^+\pi^-)$ and $\pi^+\pi^0\pi^0$ (18.2%)	0.11	0.31	0.53	0.74
$\pi^0\mu^+\nu$ (3.4%)	0.01	0.04	0.06	0.09
$\pi^0e^+\nu$ (4.8%)				<0.01
Total	0.37	1.12	1.89	2.66

with a $\chi^2=52.8$ for four d.f. The error indicated is determined only by the statistical error and the consistency within each run.

The abnormally large χ^2 is due to the fact that we are now comparing data taken at different momenta, different decay lengths, and with counters of different sizes (and thus different decay corrections). By again enlarging the error by $(\frac{1}{4}\chi^2)^{1/2}$, we obtain an error in lifetime of ±0.018 nsec, which represents the consistency of our data.

The main error in our absolute lifetime determination, however, is due to our lack of knowledge of the absolute value of the momentum. This is in contrast to the lifetime ratio where only the *relative* values of the momentum are important. We have, therefore, determined with extreme care the integral of the magentic field in magnet D_3. This was done both by mapping the field[23] and also by a floating-wire technique. We believe that the absolute momentum measurements so obtained have a maximum uncertainty of 0.2%. This error is quite large in comparison to the other

TABLE VII. Corrected attenuation for use in absolute lifetime determination referred to the first counter of each station. Data are already averaged over polarities.

Run	Momentum (GeV/c)	l (in.)	Counter	Mean
1, 2	1.6	622	S_4 0.26474±0.00042 S_5 0.26486±0.00041 S_6 0.26476±0.00041	0.26479±0.00041
3, 4	1.6	1285.7	S_8 0.06418±0.00036 S_9 0.06494±0.00022 S_{10} 0.06525±0.00017	0.06479±0.00039
5	2.0	622	S_4 0.34446±0.00038 S_5 0.34485±0.00037 S_6 0.34485±0.00038	0.34472±0.00038
6, 7	2.0	1285.7	S_8 (Reject) S_9 0.11225±0.00020 S_{10} 0.11248±0.00021	0.11236±0.00021
8	2.0	1942.9	S_{16} 0.03745±0.00027 S_{17} 0.03721±0.00018 S_{18} 0.03788±0.00021	0.03751±0.00028

[23] The internal consistency of the field measurements was better than 0.1%. However, the proximity of the last quadrupole distorted the fringing field.

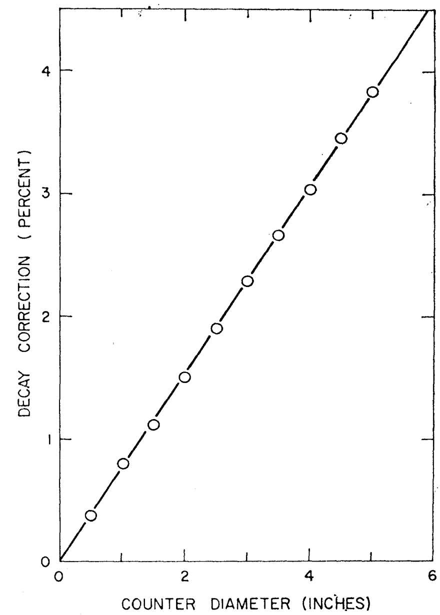

FIG. 6. Plot of the Monte Carlo results for the decay-product correction as a function of counter diameter. Note the goodness of the linear fit.

uncertainties; making allowance for a 10% error in the decay correction (~0.0014) and 0.0014 for absolute transmission and detection efficiency, we finally obtain

$$\tau(K^+)=12.272\pm0.036 \text{ nsec}. \qquad (7)$$

This result is in agreement with the accepted value of the K mean lifetime, (3, 10) and with the recent result of Ford *et al.*,[10] who find $\tau(K^+)=12.21+0.11$ nsec, but not with the measurement of Fitch *et al.*[24]

The over-all consistency of our K^+ lifetime measurement and any deviation from purely exponential decay can be determined from Fig. 7. A purely exponential

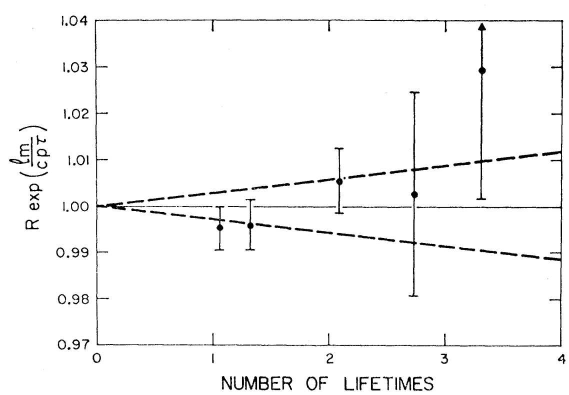

FIG. 7. Plot of the deviations from a pure exponential of the corrected attenuations of K mesons. The errors indicated are those due to statistics and internal consistency only. The lines show the variation if the lifetime τ changes by $\pm(\Delta\tau=0.036$ nsec).

[24] V. L. Fitch, C. A. Quarles, and H. C. Wilkins, Phys. Rev. **140,** B1088 (1965); they give $\tau(K^+)=12.443\pm0.038$ nsec.

TABLE VIII. Representative results obtained with positive identification of the K mesons at the end of the flight path (J counter) at 1.6 GeV/c.

Polarity	Station	Transmission[a]	Attenuation[b]
+	B	0.97626±0.00245	0.062586±0.000244
−	B	0.97653±0.00199	0.062952±0.000200

$R_+''/R_-''=0.99418$
$(\tau_+/\tau_- - 1)=(-2.13\pm2.0)\times10^{-3}$
After correction for Earth's field
$(\tau_+/\tau_- - 1)=(-1.74\pm2.0)\times10^{-3}$

[a] Corrected for Čerenkov counter efficiency and extrapolated to zero S_3 thickness.
[b] Corrected for Čerenkov counter efficiency, transmission, and extrapolated to zero S_3 thickness.

decay with a mean life $\tau=12.272$ nsec would have the points scatter statistically around the value 1.0. The dashed curves indicate the deviation if the mean life is changed by $\pm\Delta\tau=0.036$ nsec. Any long-lived component will lead to an increase of $R\exp(lm/cp\tau)$ with time. The upper limit for any long-lived (mean life $\gtrsim100$ nsec) contamination in the beam is 0.3% (90% confidence limit).

C. Other Measurements

As mentioned previously, we performed some measurements with a positive identification of the K mesons at the downstream end of the decay path, using a 4-in.-diam Čerenkov counter. Typical transmissions obtained were 0.96–0.97 caused in part to the effect of counter efficiency. The resulting lifetime ratios differ from unity by a few parts in 10^3, but in view of the low transmission and the possibility of systematic effects in detection efficiency, we have not included these data in our analysis. In Table VIII we present a summary of typical results at 1.6 and 2.0 GeV/c.

Following the K^+/K^- measurement, we also performed a measurement of the π^+/π^- lifetime ratio, with the same equipment and using the same approach; our motivation for this was to provide a check of our procedure, and also to improve on the then poorly-known π^+/π^- lifetime ratio.

Measurements were performed at 1.6 and 1.2 GeV/c including six alternations of the beam polarity. Unfortunately, due to the much smaller value of $lm/cp\tau$ for π mesons, the accuracy of these measurements is significantly lower than for the K meson. Clearly, the lifetime ratio for π mesons can be obtained with much greater precision at lower momenta. In that case, however, multiple scatterings and other considerations dictate a detection system completely different from that used here for the K mesons.

TABLE IX. Summary of the differences from unity of the lifetime ratio $(\tau_+/\tau_- - 1)$ in units of 10^{-3} for π mesons.

p (GeV/c)	Station	l (in.)	$lm/cp\tau$	Counter	$(\tau_+/\tau_- - 1)\times10^3$
1.2	B	1286	0.5	S_9	3.04±1.4
				S_{10}	4.21±1.2
1.2	C	1944	0.75	S_{17}	3.83±1.0
				S_{18}	6.13±1.0
1.6	B	1286	0.38	S_9	3.88±1.9
				S_{10}	2.40±2.0

A summary of the lifetime ratios for each run and each counter (similar to the data of Table IV) is given in Table IX for π mesons. The direct average of the six ratios of this table yields

$$\tau(\pi^+)/\tau(\pi^-)-1=+0.0023\pm0.0040. \quad (8)$$

This result has been since significantly improved by the recent measurement of a University of California group[8] which finds

$$\tau(\pi^+)/\tau(\pi^-)-1=+0.00064\pm0.00069.$$

To attempt an absolute determination of the pion lifetime from these data is even more difficult. This is due (a) to the much larger decay-product correction, since the angle of the decay μ mesons is much smaller, (b) to the difficulty of separating the μ mesons from the beam at these momenta,[25] and (c) to the fact that it was operationally difficult for us to reduce the beam to a low counting level without destroying its phase-space properties.

Finally, we note that from an antiproton transmission measurement we can set an upper limit for the decay rate of the antiproton:

$$\Gamma(\bar{p}\text{ decay})<2\times10^{-4}\text{ sec}^{-1}. \quad (9)$$

V. DISCUSSION

The question of the validity of the CPT theorem is of extreme importance. Since C, P, and CP violation have so far been discovered only in the weak interactions, it is natural to search for CPT violations in this field; and while different tests of CPT can be devised,[26] the lifetime equality of particle and antiparticle has so far provided the most sensitive experimental checks.

At present, the limit of sensitivity is at one part in 10^3 or slightly below, and it is interesting to contemplate whether such measurements can be substantially improved. Clearly, a direct experimental measurement of the *difference in lifetimes* would be desirable. On the other hand, comparison measurements, such as reported here, could perhaps be extended by an order of magnitude for π mesons where fluxes compatible with such high statistical accuracy are available.

In that case, however, systematic effects pretaining mainly to the knowledge of momentum and distance to

[25] We used a differential gas Čerenkov counter which showed a clear muon peak, but nevertheless we estimate a muon contamination of 1/1000 under the pion peak.

[26] A detailed discussion of possible tests of CPT invariance is given, e.g., by T. D. Lee and C. S. Wu, Ann. Rev. Nucl. Sci. **15**, 381 (1965).

one part in 10^4 become dominant. One way to circumvent this problem is to use a measuring system with trajectories that are isochronous (in proper time), namely, such that l/p is constant. Clearly, a uniform magnetic field fulfills this condition. However, the system must have focusing properties, since long decay paths will be involved, and in addition, it must be achromatic over the nomemtum band accepted, which realistically will be $\Delta p/p \approx 0.005$. Such systems can be realized, but it is still questionable that in practice lifetime differences of the order of 10^{-4} can be measured by a direct comparison of the decay of beams of charged particles.

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Search for $S=+1$ Baryon States in Photoproduction*

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A search has been carried out for $S=+1$ baryon states (Z particles) in photoproduction on hydrogen with a missing-mass spectrometer by analyzing the structure in the K^- yield as a function of end-point bremsstrahlung energy for fixed laboratory production angles and momentum. Data were taken at the three laboratory angles $\theta_K=10°$, 15°, and 20° to check the predictable kinematic behavior of two-body final-state reactions. The synchrotron energy was varied from 3.5 to 6.0 BeV, which corresponds to a missing-mass range of 1.6–2.5 BeV for a laboratory momentum of 2.5 BeV/c. A fit to the excitation function at $\theta_K=10°$ suggests structure in addition to a smooth background, while the $\theta_K=15°$ data can be adequately fitted with a smooth background alone. Upper limits for photoproduction cross sections for each $S=+1$ state at $\theta_K=10°$ and 15° are, respectively, 20 and 4 nb/sr in the center-of-mass system.

1. INTRODUCTION

In recent years, searches for strangeness $S=+1$ baryon states (Z particles) have been carried out in a number of different reactions.[1–3] Though such a baryon state would fit within an $SU(3)$ classification, it would be particularly interesting, since it would require a $\overline{10}$ or higher-order representation. Moreover, in the quark model, such a state would require at least a five-quark structure rather than a three-quark structure which is adequate to represent the well-established baryon states.

The first evidence suggesting the existence of $S=+1$ baryon states appeared in measurements[4,5] of the total cross section for K^+-p and K^+-d scattering in the K^+-meson momentum range 1.0–3.5 BeV/c. Structure in these cross sections was found for center-of-mass energies of 1910, 2190, and 2505 MeV. Recently, measurements of elastic scattering of K^+ mesons from protons at large angles for the meson momentum range 1–2.5 BeV/c indicate a possible resonance in the K^+-p system at a mass of approximately 2000 MeV in a $P_{1/2}$ state.[6,7] Also, measurements of the elastic differential cross section and asymmetry parameter for scattering of K^- mesons on polarized protons in backward directions, in conjunction with a Reggeized baryon-exchange model, indicate the possible exchange of a Z particle.[8]

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