Heavy Meson Lifetimes*

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Two identical nuclear emulsion stacks were exposed at different distances to the 114-Mev Bevatron K^+-beam using the same geometry and Bevatron conditions. A comparison of the K_L to τ-meson ratios in the two stacks combined with the known lifetimes of the $K_{\pi 2}$ and $K_{\mu 2}$ gives $(1.18_{-0.28}^{+0.55})\times 10^{-8}$ sec for the τ^+ lifetime. The ratio of the $K_{\pi 2}^+$ to the τ^+ lifetime is then 1.03 with a root-mean-square error of $\pm 29\%$. Thus the τ and the $K_{\pi 2}$, which according to Dalitz-type analysis should be different particles, have the same lifetime within experimental errors. The τ and K_L lifetimes can be obtained by a second method which does not rely on any previous lifetime information. In this method the ratios of the heavy meson fluxes to the proton and pion beam fluxes are compared. The results obtained by this method are $(1.04_{-0.23}^{+0.42})\times 10^{-8}$ sec for the τ^+ lifetime and $(1.11_{-0.11}^{+0.18})\times 10^{-8}$ sec for the K_L^+ lifetime. Alternate τ and $K_{\mu 3}$ fluxes in the two stacks also indicate a lifetime of about 10^{-8} sec.

I. INTRODUCTION

EXCEPT for a spin-parity difference, the τ and θ mesons so far appear to be the same particle. All experimental data thus far give the same mass,[1,2] abundance ratios,[1–4] and interactions with heavy nuclei.[5,6] Because the analysis of τ decays requires that the τ and θ should have different spin and parity combinations,[7,8] it is important to search for some other experimental difference. In this experiment the lifetimes of the τ^+ and θ^+ are compared by measuring the K_L to τ ratios at two different distances from the Bevatron target. Figure 1 shows the two positions in which emulsion stacks were exposed using the same copper target with 6.2-Bev protons. Preliminary results based on a partial scanning of these stacks were reported in a previous letter.[9] The additional statistics has given rise to changes in the lifetime values which are not unreasonable.

Our result for the ratio of the θ^+ (the terms θ^+ and $K_{\pi 2}$ are used interchangeably) to the τ^+ lifetime is (1.03 ± 0.30). This is based on the $K_{\pi 2}$ and $K_{\mu 2}$ lifetimes obtained by groups at Princeton[10] and Berkeley[11] using delayed-coincidence techniques. Using the Princeton and Berkeley weighted mean of 1.18×10^{-8} sec for the lifetime of the K_L ($K_{\pi 2}$ and the $K_{\mu 2}$), our result for the τ lifetime is

$$T_\tau = (1.18_{-0.28}^{+0.55})\times 10^{-8} \text{ sec.} \quad (1)$$

The notation "T" is used for mean life rather than half-life.

In addition, this experiment provides an independent determination of the lifetimes by comparing the heavy meson fluxes with the beam pions and protons of the same momentum in the two stacks. This result is $T_\tau = (1.04_{-0.23}^{+0.42})\times 10^{-8}$ sec and $T_{K_L} = (1.11_{-0.11}^{+0.18})\times 10^{-8}$ sec. Also it was possible to obtain some information on the $K_{\mu 3}$ and alternate τ lifetimes. Figure 2 is a plot of the relative probability that our results turn out the way they did if one assumes various lifetime values for the τ, $K_{\mu 3}$, and τ'. Our results suggest that all types of heavy mesons have the same lifetime.

These results make the Weinstein-type explanation[12] for the identity of the τ and θ lifetimes more difficult. In this case the interaction between air and τ or θ mesons must be so large that there would be more than one transition of $\tau \rightleftarrows \theta$ per 6 feet of air.

II. EXPERIMENTAL DETAILS

The two stack positions are shown in Fig. 1. In both cases the average beam momentum was 356 Mev/c and 6.2-Bev protons were used on the same copper target. Each stack consisted of 39 Ilford G5 pellicles, 6 inches$\times$7 inches$\times$600 microns. The stack positions were 70 inches apart, which corresponds to 0.82×10^{-8} sec in the K-meson rest system. The beam fluxes per cm^2 for both stacks are given in Table I. Except for 28 of the τ mesons found by area scanning in stack A, all of the data were obtained by track scanning which involves following gray tracks starting at a distance corresponding to 1.6 cm residual range for K mesons.

The track scanning in stack A gave 625 K_L, 25 τ, 9 τ', and 6 $K_{\mu 3}$. Track scanning of the entire usable

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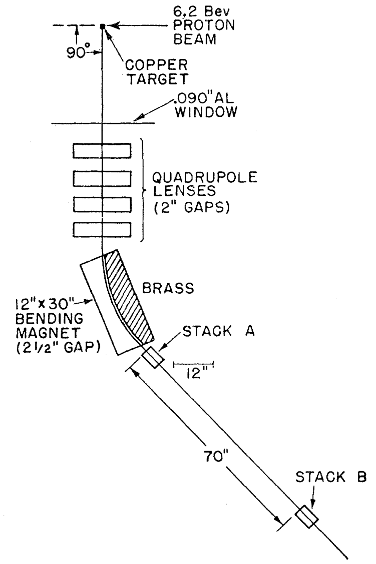

FIG. 1. Experimental setup used at the Bevatron.

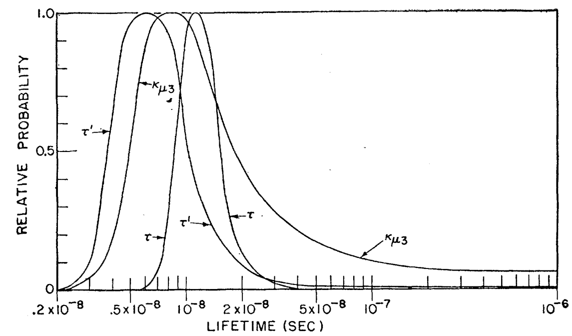

FIG. 2. The likelihood functions for the $K_{\mu3}$, τ', and τ lifetimes. For example, any point on the $K_{\mu3}$ curve represents the probability of getting our results assuming that lifetime value, divided by the probability of getting our results assuming $T_{K\mu3}=0.83\times10^{-8}$ sec.

region in stack B gave 548 K_L, 28 τ, 4 τ', and 4 $K_{\mu3}$. In most of the track scanning, all gray tracks within specified azimuth and dip angle limits were followed. However, a smaller portion of the stack-A data was obtained by a faster type of track scanning in which the scanner was free to use more rigid limits of angle, grain density, and visual scattering. Data obtained by this fast track scanning technique are used only in the case when the τ lifetime is obtained by the method of comparing K_L to τ ratios in combination with the known K_L lifetime.

The fastest method for improving the statistics on the τ flux in stack A was area scanning. The area-scanning limits in the beam direction covered a region in which $(75\pm2)\%$ of the heavy mesons end, as determined from the track-scanning data. Scanning efficiency was continuously checked by independent rescanning of the pickup strips and refollowing of tracks not recorded by both scanners. The loss rate for the first scanning was found to be less than 5%. We feel that scanning efficiency was so high that it could not introduce any systematic errors in our lifetime results. In the cases where endings were found without secondaries, the primaries were grain-counted at 1.5 cm residual range in stack A and 2.0 cm in stack B. This made it possible to separate proton endings from those K_L endings where the secondaries were not found.

In order to increase the $K_{\mu3}$ and τ' statistics, all K secondaries in both stacks with a dip less than $\pm41°$ original angle were blob-counted. In this region of dip we expect a high detection efficiency for $K_{\mu3}$ secondaries under 29 Mev and τ' secondaries under 38 Mev. The $K_{\mu3}$'s found in this region of dip angle had energies of 11.3, 16.5, 19.8, 21.5, 27.2, 37 ± 4, and 40.0 Mev. The alternate τ's in this region of dip had energies of 8.3, 12.3, 26.6, 32.3, 37.1, and 38.7 Mev. In the region of dip greater than $\pm41°$ we expect high efficiency for $K_{\mu3}$'s under 20 Mev and alternate τ's under 28 Mev. In this region the $K_{\mu3}$'s had energies of 19.3, 19.4, and 21.4 Mev, and the alternate τ's had energies of 6.4, 12.9, 17.2, 26.1, 34.9, 36 ± 3, and 49 ± 6 Mev. Errors are $\sim\pm3\%$, unless otherwise stated. Of the 23 heavy secondaries found, three left the stack before ending. In these three cases the identity and energy of the secondary was established by grain counting *vs* residual range.

III. ANALYSIS OF RESULTS

Method 1

The τ lifetime, T_τ, is obtained from the following relations:

$$R_\tau=C\exp(-0.82\times10^{-8}/T_\tau),$$
$$R_K=C\exp(-0.82\times10^{-8}/T_K), \quad (2)$$

where R stands for the ratio of particles per cm² found in stack B to that found in stack A. The constant C is determined by the relative exposure times and geometries. It is the same for all particles of the same mass. The value 0.82×10^{-8} used in Eq. (2) is the travel time from stack A to B in the K-meson rest system. The following formula is obtained by using the value $T_K=1.18\times10^{-8}$ sec[9,10] in Eq. (2):

$$T_\tau=[0.845+1.22\ln(R_K/R_\tau)]^{-1}\times10^{-8}\text{ sec.} \quad (3)$$

The K_L to τ ratio obtained by track scanning in stack B is $19.5(1\pm0.19)$. The combined K_L to τ ratio in stack A obtained by track scanning, area scanning, and fast track scanning is $19.5(1\pm0.15)$. The fact that these ratios are the same within statistics means that our lifetime results for the τ and K_L must be the same within statistics. The following lifetime values were obtained by using Eq. 3:

$$T_\tau=(1.18_{-0.28}^{+0.55})\times10^{-8}\text{ sec},$$
$$T_{K\mu3}=0.83\times10^{-8}\text{ sec}, \quad (4)$$
$$T_{\tau'}=0.60\times10^{-8}\text{ sec}.$$

TABLE I. Particle fluxes per cm² in Bevatron K-meson beam.

Stack	Target distance in inches	Number of protons on Bevatron target	Beam protons per cm²	Beam pions per cm²	K_L flux per cm²	τ flux per cm²
A	108	4.2×10^{12}	$(3.46\pm0.09)\times10^{5}$	$(9.14\pm0.29)\times10^{4}$	830 ± 36	44.8 ± 6.7
B	178	6.0×10^{12}	$(7.65\pm0.31)\times10^{4}$	$(1.79\pm0.12)\times10^{4}$	85.0 ± 3.4	4.35 ± 0.82

The errors on the τ lifetime are the statistical root-mean-square deviations. Small contributions due to systematic uncertainties are included.

Because of the small statistics, it would not be very meaningful to present "errors" on the $K_{\mu3}$ and τ' lifetimes. Instead, we have calculated the lifelihood or "relative probability" curves for all possible lifetime values from 10^{-9} to 10^{-6} sec for the $K_{\mu3}$ and τ'. This is shown in Fig. 2 along with the corresponding curve for the τ. For example, the $K_{\mu3}$ curve represents the relative probability that one should find 6 $K_{\mu3}$'s in stack A and 4 in stack B when the $K_{\mu3}$ lifetime has the value as given on the abscissa. Actually this probability is a function of both $T_{K_{\mu3}}$ and $\bar{N}_A$, the value one chooses for the relative abundance or the average number of $K_{\mu3}$'s which should be found in stack A if the experiment were repeated many times. The complete presentation of our information on the $K_{\mu3}$ lifetime would be a 3-dimensional plot of $P(\bar{N}_A,T_{K_{\mu3}})$ *vs* both $\bar{N}_A$ and $T_{K_{\mu3}}$, where P is the relative probability or likelihood function. Actually Fig. 2 is a plot of this function for $\bar{N}_A=6.0$ only. Other choices of $\bar{N}_A$ give curves of similar type with lower heights. The curve of the function $P'(T_{K_{\mu3}})=\int_0^\infty P(\bar{N}_A,T_{K_{\mu3}})d\bar{N}_A$ looks almost the same as the curve in Fig. 2. Exactly the same procedure was used in obtaining the curve for the τ'. If the 20% probabilities are taken as limits, then $0.4\times10^{-8}<T_{K_{\mu3}}<4\times10^{-8}$ sec and $0.35\times10^{-8}<T_{\tau'}<1.5\times10^{-8}$ sec.

Another by-product of this experiment is a determination of the relative abundance of τ mesons. We obtain 0.050 ± 0.006 as the fraction of heavy mesons which decay to 3 charged pions.

Method 2

The preceding analysis made use of other lifetime values obtained by counters[9,10] in combination with our K to τ ratios in order to establish the τ lifetime. An independent approach is to normalize our K and τ fluxes to the beam proton or pion[13] fluxes found in stacks A and B. Then the τ and K_L lifetimes can be determined without making use of any other results. This method is dependent upon the assumption that the experimental geometry used affects particles of different mass in the same way, as long as the momenta are the same. If this assumption were correct, the proton-to-pion ratios in both stacks should be the same. The observed proton to pion ratios are 3.80 ± 0.15 in stack A and 4.28 ± 0.33 in stack B, a $(12\pm9)\%$ difference. It is not surprising to find some difference in the two ratios, since the multiple scattering angle in the Bevatron window (0.09 inch aluminum) goes as $1/p\beta$, and β is quite different for protons and pions of 356 Mev/c. Fortunately the difference in our proton-to-pion ratios is so small that it doesn't have much effect in the lifetime determination. The extent of this uncertainty can be seen by calculating the τ lifetime three ways: (a) based on the proton fluxes only, (b) based on the pion fluxes only, and (c) based on an interpolated flux ratio for a particle of mass 493 Mev, where the small discrepancy in proton and pion flux ratios is assumed to be due to multiple scattering in the window. The respective τ lifetime results are 0.995, 1.16, and 1.04×10^{-8} sec when one uses the following equation:

$$R_\tau/R=\exp(-0.82\times10^{-8}/T_\tau), \tag{5}$$

where $R=0.219$ for the proton stack B to stack A ratio, $R=0.194$ for the pions, and $R=0.211$ for the interpolated value. The values used for R_τ and R_{K_L} are obtained from Table I and do not include the fast track-scanning data. The τ and K_L lifetimes and their rms errors obtained in this way are

$$\begin{aligned} T_\tau&=(1.04_{-0.23}^{+0.42})\times10^{-8}\text{ sec},\\ T_{K_L}&=(1.11_{-0.11}^{+0.18})\times10^{-8}\text{ sec}. \end{aligned} \tag{6}$$

IV. CONCLUSIONS

The τ lifetime values obtained by methods 1 and 2 are in good agreement. Our value of 1.11×10^{-8} sec for the K_L lifetime agrees well within the errors with the value of 1.18×10^{-8} sec obtained by counter techniques.[9,10] Our values of the τ lifetime are in agreement with the earlier determination of Alvarez and Goldhaber, who obtained $(1.0_{-0.3}^{+0.7})\times10^{-8}$ sec using emulsions 11 inches from the Bevatron target without magnetic analysis.[14] The combined results of all lifetime experiments suggest that the charged τ, θ, $K_{\mu2}$, $K_{\mu3}$, and τ' all have the same lifetime. So far the only observed difference in these particles is the spin-parity difference of the τ and θ decay products.[7,8]

Several explanations have been proposed for the "identical" lifetimes of the τ and θ.[12,15,16] Since in this

[13] The stack B pion flux has been corrected for the small depletion of the pion beam due to decay in flight. In the 70-inch path, 9% of the pions decay. In about half of these decays, the decay muons are still in the beam direction and are counted as pions.

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experiment the particles decayed while in air, the Weinstein[12] explanation would require the reaction $\tau \rightleftarrows \theta$ to have a cross section over 300 times geometrical for K mesons of velocity $\beta = 0.59$ in air. The cascade scheme of Lee and Orear,[15] which still lacks any experimental verification, becomes less reasonable as the $\tau - \theta$ mass difference becomes smaller. Lee and Yang[16] have recently proposed that there may be only one heavy meson of a certain spin and parity, but that its parity is not conserved when it decays. They point out that one can postulate nonconservation of parity for all weak interactions without contradicting experiment.

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Inelastic and Elastic Scattering of 187-Mev Electrons from Selected Even-Even Nuclei*

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A survey has been made of the differential scattering cross sections for 187-Mev electrons on the even-even nuclei $_{12}Mg^{24}$, $_{14}Si^{28}$, $_{16}S^{32}$, $_{18}A^{40}$, and $_{38}Sr^{88}$. It has been possible to separate the elastic scattering from the inelastic in all cases and to resolve the inelastic groups from specific nuclear levels for at least one level in all cases. A simple Born-approximation analysis of the elastic data yields values of the effective radii and surface thicknesses of the nuclear charge densities which (if suitably corrected for failure of the Born approximation) are in substantial agreement with the results of Hahn, Ravenhall, and Hofstadter; i.e., a radius parameter of $c \cong 1.08\ A^{\frac{1}{3}} \times 10^{-13}$ cm (radius to half-maximum of the charge distribution) and a surface thickness of $t \cong 2.5 \times 10^{-13}$ cm (thickness from 10% to 90% of the maximum of the charge distribution). Phenomenological analysis of the inelastic scattering along the lines laid down by Schiff yields some tentative multipolarity assignments, and application of some results of Ravenhall yields estimates of (radiative) partial level widths; for the $E2$ transitions these correspond to lifetimes of $\sim 19 \times 10^{-13}$ sec (Mg 1.37 Mev) to $\sim 1.4 \times 10^{-13}$ sec (Sr 1.85 Mev). The observed strengths of the transitions are compared to those predicted by Weisskopf theory.

I. INTRODUCTION

THE elastic scattering of high-energy electrons by atomic nuclei has been the subject of considerable experimental study.[1–8] Recently it has been possible in this laboratory to observe certain examples of inelastic scattering[9–11] in which the incident high-energy electron is scattered with the loss of a discrete quantum of energy corresponding to the excitation of a level in the target nucleus.

The present experiments were initiated as a survey of the inelastic and elastic scattering from even-even nuclei in the region of intermediate atomic numbers. These target materials were chosen for a number of reasons: First, most of them are known from gamma-ray spectroscopy, angular correlations, etc., to have easily excited low-lying levels with spacings on the order of a few Mev, which should be resolvable in an experiment of the type of Fregeau and Hofstadter.[11] Second, the principal isotope of most of these elements occurs in high abundance, so that the natural form may be used in the targets. Third, the ground state has zero spin and even parity in the known cases (see, e.g., Endt and Kluyver[12] and probably in all cases (i.e., from shell-structure arguments); furthermore, it usually happens[12–14] that one or more or the lower levels has known total angular momentum and a parity consistent with electric-type multipole transitions from the ground state. This last point is important because the

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