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ABSTRACT

Our program of measuring meson masses has been extended to the positive τ, $K_{\mu 2}$, $K_{\pi 2}$, $K_{\mu 3}$, and τ' particles. With the Bevatron as a source, and employing a modification of the Kerth-Stork quadrupole lens and analyzing-magnet arrangement, we have obtained a mass resolution of 1.6% for an individual particle. Using the stopping behavior or the grain density of the secondary for K-particle classification, and the multiple scattering as a check, we obtained practically pure samples of the above types of K mesons for analysis. The particles were compared directly with protons of the same momentum, and also with the τ meson, the mass of which is known accurately. Relative to the mean τ mass of 966 we obtain the following results, all in electron mass units: τ (966 ± 3.1), $K_{\mu 2}$(962.5 ± 3.2), $K_{\pi 2}$(972.2 ± 4.7), $K_{\mu 3}$(951.2 ± 10.6), τ'(951.5 ± 10.9). These are all consistent with a single K mass of 966. The results are independent of the range-momentum relation; however, the intercomparison of the masses measured relative to the τ meson and relative to the proton check closely, indicating that there are no large systematic errors and that the shape of the range-momentum relation must be nearly correct.

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The meson-mass measurement program[1] that was started some years ago now has been extended to several types of K mesons. Although a number of important parts of the new work remain to be completed, particularly studies of the energy-momentum balance in the various decay schemes, the current interest in the K meson mass(es), and the conflicting results that have been obtained,[2] prompt us to make this preliminary report.

After experimenting with other geometries, we developed our apparatus from the basic design of Kerth and Stork.[3] With this arrangement the particles from a Bevatron target pass first through a strong-focusing lens and then through an analyzing magnetic field before detection in a stack of emulsion. Unfortunately, a window through which the particles must pass in emerging from the vacuum chamber, and several feet of air path, each cause considerable multiple scattering of the beam and reduce the efficiency and momentum resolution of the strong-focusing lens. To improve the momentum selection obtained with the original apparatus we redefined the particle orbits by introducing a 6-inch lead collimator containing a 0.25-inch vertical slit preceding the analyzing magnet. The stretched-wire technique was used to check the rather critical line-up of the collimator. Also, to reduce the multiple scattering and energy loss of the particles while traversing the analyzing magnet, the air in the path between the collimator and detector was replaced by helium. The result of these various improvements was to substantially better the momentum resolution. The effect of the momentum interval on the mass resolution was reduced so as to become comparable to the effect of the inherent straggling of ranges.

In this work the rectified particle track length R was measured for each identified particle. The ranges were determined by measuring the length of each segment of track that could be considered straight and adding the lengths together. Since the edge of the emulsion is distorted in processing, provision was made for correctly determining its original location. The surface of the stack upon which the particles are incident nearly normally was milled flat, and sharp V-shaped grooves were cut in the side of the stack. Before processing, a 1-millimeter rectangular grid was contact-printed on each pellicle in a position determined to within less than 20 microns by the machined features of the pellicle. After processing, the grid constituted a coordinate frame, not only for the location of events but also to define the edge. Use was also made of the fact that in addition to pions, K particles, and protons, there are deuterons, tritons, He^3, and He^4 particles as abundant constituents of the beam. Since all the particle orbits entering the emulsion stack at the same point have the same magnetic rigidity, the depths to which the various particles penetrate give precise information on the edge correction.

In order to avoid bias in the selection of K particles for measurement, the emulsion was scanned along a band where the τ meson was expected to have a residual range of about 1.5 cm. Each non-minimum track found within 10° of the expected direction of the K-particle tracks was followed until it stopped, or was identified as a proton.

The behavior of the secondary particles into which they decay provided the basis of classification of the K particles; it had been assumed from the beginning that mass measurements would be meaningful only for mesons identified as to type. The development of the emulsion was remarkably uniform, and it was found that if 400 grains were counted in tracks dipping less than 15° a separation of better than 95% could be effected between the $K_{\mu 2}$ mesons (1.05 x min) and the $K_{\pi 2}$ mesons (1.21 x min). These types, along with the τ mesons, constitute the bulk of the particles found. All secondaries ionizing more intensely than those of the $K_{\pi 2}$ were followed until they stopped or left the stack. The τ'

has one positive pion of low energy (<53.9 Mev) as a secondary. The $K_{\mu 3}$ is recognized by the presence of a muon secondary, the energy of which is lower than that of the secondary from the $K_{\mu 2}$. In this way four $K_{\mu 3}$ and four τ' particles were identified.

In Fig. 1 is shown the grain densities (actually "blob" densities) of the secondaries plotted as a function of the dip angle δ. It is noteworthy that the observed grain density does not vary strictly in proportion to sec δ, presumably partly because of an influence of the random background grains. The separation achieved by the grain counting is perhaps even slightly better than expected. No bias was detected in the method of recording the data, and the multiple scattering of 20 particles classified by grain density as $K_{\mu 2}$ secondaries confirmed this classification.

The multiple-scattering work was carried out both to insure the purity of the sample of $K_{\mu 2}$ mesons and to look for K_{e3} particles, since the electron secondary cannot be distinguished from the $K_{\mu 2}$ secondary by grain count alone. The criteria used to select a secondary for a multiple-scattering measurement were that it have a dip angle δ less than 10° and be at least one centimeter from the edge of the emulsion. In order that the noise correction to the observed scattering be small, a cell of sufficient length to insure a signal-to-noise ratio of at least 4 to 1 is required. In these measurements, a 300 μ cell length met this condition. With this cell length and a velocity of 0.91c (the velocity of the $K_{\mu 2}$ secondary) the scattering factor K_{co} ^{4} is 25.5 Mev deg. After the second differences were measured by the Fowler technique, the procedure used to eliminate large single-scattering events was to discard all measurements that exceed four times the resultant mean. About 65 cells were used to estimate the pβc of each secondary. The mean of the second differences then has a standard deviation of about 10%. With this precision, electron secondaries of $p\beta c < 150$ Mev could easily be detected. While the secondary from the $K_{\pi 2}$ meson ($p\beta c = 169.6$ Mev) could not be so readily identified, the probability would be 0.65 of resolving it from the μ-meson distribution if even one such event were present in the sample that was multiply scattered. Of the 20 secondaries measured, all were consistent with being muons from the decay of the $K_{\mu 2}$ meson. The mean $p\beta c$ of all events was 214.0 ± 3.4 Mev, which agrees well with the calculated value of 214.8 Mev, assuming the $K_{\mu 2}$ mass to be 966 me. This measurement tends to confirm the correctness of the scattering factor. We have also concluded from these results that the fraction of Ke_3's among the $K_{\mu 2}$'s is probably less than 5%. In addition the data give support to the validity of grain counting as a method to separate the $K_{\mu 2}$ and $K_{\pi 2}$ modes of decay.

By using the means described we have identified τ, τ', $K_{\mu 3}$, $K_{\pi 2}$ and $K_{\mu 2}$ mesons in the detecting emulsion. Since the proper time of flight to the stack is $\approx 1.2 \times 10^{-8}$ second, none of their lifetimes can be short compared to 10^{-8} second unless they themselves are decay products of a long-lived parent. In the latter event the mass being measured in this experiment is that of the parent.* As the detection efficiencies for the particles with different types of secondaries are not equal, and yet to be determined, the relative numbers of the classified K particles do not of course reflect the relative populations of the various K particles that survive 10^{-8} second. The mesons were produced by bombarding a tantalum target with protons of 4.8 Bev.

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*This possibility was pointed out by Luis W. Alvarez in connection with a decay scheme proposed by C. N. Yang.

The mass analysis was carried out by introducing the "Standard Range" R_o. This is the range (as deduced from the observed proton ranges using the range-momentum relation[5]) that a particle of mass 966 Me would be expected to have. It is, of course, a function of the point of entry into the stack. This range is introduced chiefly as a computational device: an error in its choice affects the final mass values only in a second approximation. For each measured range a quantity $\Delta R/R_o = (R - R_o)/R_o$ may be calculated. Since the percentage range straggling[6] is almost independent of the velocity in this region and if the momentum interval is not large, the quantity $\Delta R/R_o$ for a particle of a given mass (near 966 me) should have a distribution that is nearly gaussian, with a standard deviation determined by the inherent range straggling and the momentum interval accepted. If the range-momentum relation is strictly correct and the true mass of the particle is 966 me, then the mean value of $\Delta R/R_o$ should be zero. Regardless of whether or not the range-momentum relation is correct, the mean value of $\Delta R/R_o$ will be the same for all particles of the same mass. For τ mesons which are known[7,1] to have a mass of 966.0 ± 0.6 me, the mean value $\langle \Delta R/R_o \rangle$ measures the error in the range-momentum relation used as well as other systematic effects that are common to all particles. When the mean value of $\Delta R/Ro$ is not zero, we calculate the mass equivalent ΔM of this deviation by using the formula

$$\Delta M = \frac{966}{1-q} \langle \Delta R/R_o \rangle \ . \qquad (1)$$

Here $q = p/R \frac{dR}{dp}$, where p is the momentum. In the velocity interval employed in this experiment $q \approx 3$. Then if the value of ΔM measured for the τ meson is made to correspond with the mass 966, the masses of all other particles are related directly to the τ meson.

We wish to point out that to measure a mass in an experiment such as this, the averaging of masses determined for individual particles is usually incorrect. The mass-distribution function is unsymmetrical, so that the median, mode, and mean are quite different quantities. The average obtained from a symmetrically (preferably normally) distributed function of the mass is the most useful quantity from which to derive a valid mass estimate.

For each type of K particle classified as to mode of decay, points relating "rectified range" and position of entrance were plotted. This is illustrated by Fig. 2. Superimposed on the range-vs-position data is the Standard Range curve. As described above, a systematic range correction of $+208 \pm 64\mu$ was applied to all measured ranges. The apparent shrinkage of the edge of the emulsion is caused primarily by the distortion of the edge in processing. Another factor in the shrinkage may be the drying out of the edges of the emulsion stack between the times of its exposure and the mounting upon glass.

Figure 3 shows the histograms of $\frac{R - R_0}{R_0} = \frac{\Delta R}{R_0}$ for each type of K particle. The events that are more than 2.81 standard deviations from the mean of the combined data were discarded in calculating the mean values. Of the real events, 99.5% should then be included in the analysis. The directions of all particles were measured as they entered the stack at a point just inside the region of edge distortion. At this depth in the stack the track direction is already partially lost by multiple scattering, but of the five particles discarded because the range was anomalous, three were found to have such anomalous angles that it was unlikely that they could have come directly through the collimating slit to the stack. The resultant standard deviation in the ranges is 4.74%. This range variance can be accounted for by assuming a 1.5% momentum resolution in addition to the 1.5% inherent range straggle of the K particles. The observed momentum interval is about 0.5% greater than expected when it is assumed that the particles come directly from the 1/4-inch target. This increase of momentum spread is probably caused by the multiple scattering in the 0.090-inch aluminum window of the Bevatron and the 5 feet of air path traversed before entering the 1/4-inch collimator. The multiple scattering would tend to make the source of particles appear diffused and not defined by the dimensions of the target. With the resolution we have obtained in this experiment, the probable error of a single K-mass measurement is 1.6%.

In Table I are the tabulated results of the experiment. The mass values of the K particles with their probable errors are plotted in Fig. 4.

We agree with the amended[8] result of Robert Birge et al., who find that with their resolution the mean mass of K particles with a near-minimum secondary is indistinguishable from the τ-meson mass. In addition we are able to make a stronger statement: namely, that with somewhat better mass resolution, each individual type of K meson (classified by the behavior of the secondaries) remains indistinguishable from the τ meson. All the K masses are consistent with a single value, 966 me. We also find that the range-momentum relation probably is not seriously in error, because, by making careful correction for systematic effects, we obtain close to the predicted range ratio for protons and τ-mesons.

Our result for the $K_{\mu 2}$ meson is not consistent with the low values found by several[9] cloud chamber groups when they deduce the $K_{\mu 2}$ mass from the range of the secondary. The results on the multiple scattering of the secondaries confirms our high mass of the $K_{\mu 2}$ mesons. We have calculated, using the formula of Eguchi,[10] the approximate energy loss in radiative decay of the $K_{\mu 2}$ particle, and find that it is insufficient to cause the discrepancy. However, it will in rare instances give rise to an event which phenomenologically is a $K_{\mu 3}$ decay.

As another part of our program of precise emulsion measurements, we are determining the range-momentum relation for magnetically analyzed pions and protons in emulsion stacks of accurately known density. It is believed that this program may be important for resolving the present inconsistencies and for further progress in the elaboration of the K-meson decay schemes.

The success of this mass measurement program was determined in a large measure by the technical competence and conscientious labor of Mrs. Nancy Freed, Miss Hester Lowe, Mrs. Roberta Speer, Mr. John Dyer, and Mr. James Gray, who carried out most of the scanning and measurements. We are also indebted to Mr. Leroy Kerth for information in connection with the equipment and to Dr. Edward Lofgren and the operating crew of the Bevatron, both for the bombardments and for cooperation in setting up the equipment.

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TABLE I

Type	Assumed Mode of Decay	Number	ΔM	Mass Relative to Mean τ Mass (966)	Probable Error
τ	$\pi^+ + \pi^+ + \pi^-$	27	4.2	966	3.1
$K_{\mu 2}$	$\mu^+ + \nu$	36	0.7	962.5	3.2
$K_{\pi 2}$	$\pi^+ + \pi^0$	12	10.4	972.2	4.7
τ'	$\pi^+ + \pi^0 + \pi^0$	3	-10.3	951.5	10.9
$K_{\mu 3}$	$\mu^+ + ? + ?$	3	-10.6	951.2	10.6
All Events		81	2.4	964.2	1.7
τ (Relative to Protons)			0.0	961.8	2.6

Table I. Tabulation of mass values for the τ, τ', $K_{\pi 2}$, $K_{\mu 2}$, and $K_{\mu 3}$ mesons. The probable errors of ΔM and the mass relative to the mean τ mass are the same and are listed in the last column. All masses are given in units of the electron mass.

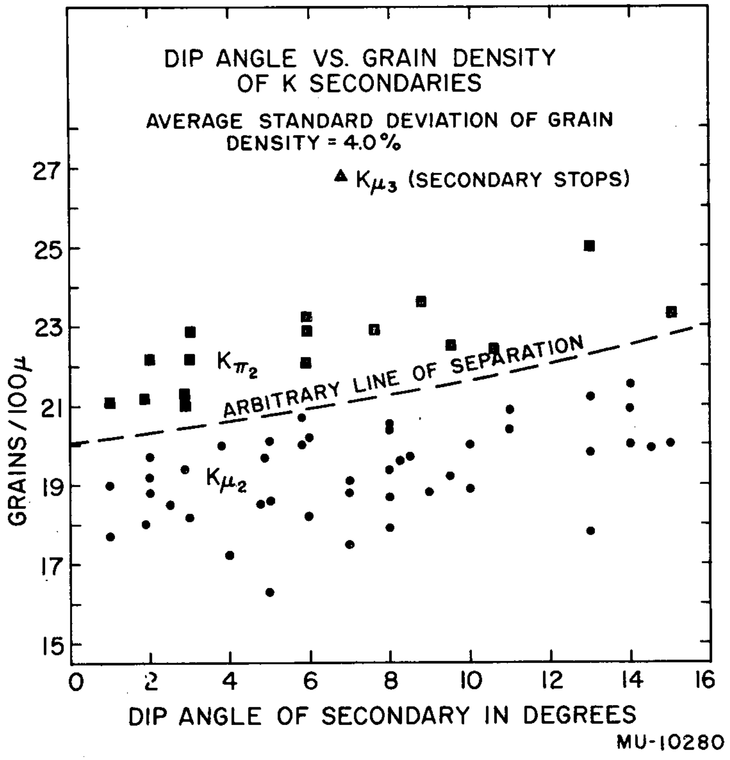

Fig. 1. Grain densities of secondaries as a function of dip angle δ . Events below the arbitrary line of separation are classified as $K_{\mu 2}$'s, those above as $K_{\pi 2}$'s. The secondary with the exceptionally high grain count stopped in the emulsion stack and was identified as a muon from the decay of a $K_{\mu 3}$ particle.

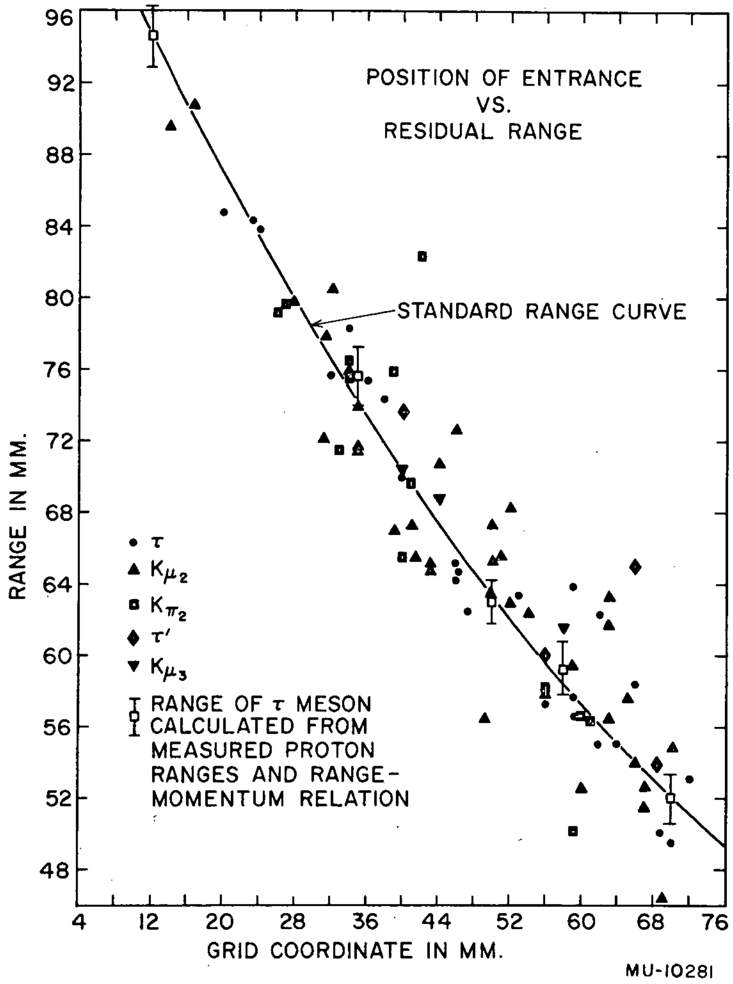

Fig. 2. Ranges of K mesons as a function of position of entrance along front edge of stack. The grid coordinate refers to the millimeter grid that is contact-printed on each emulsion.

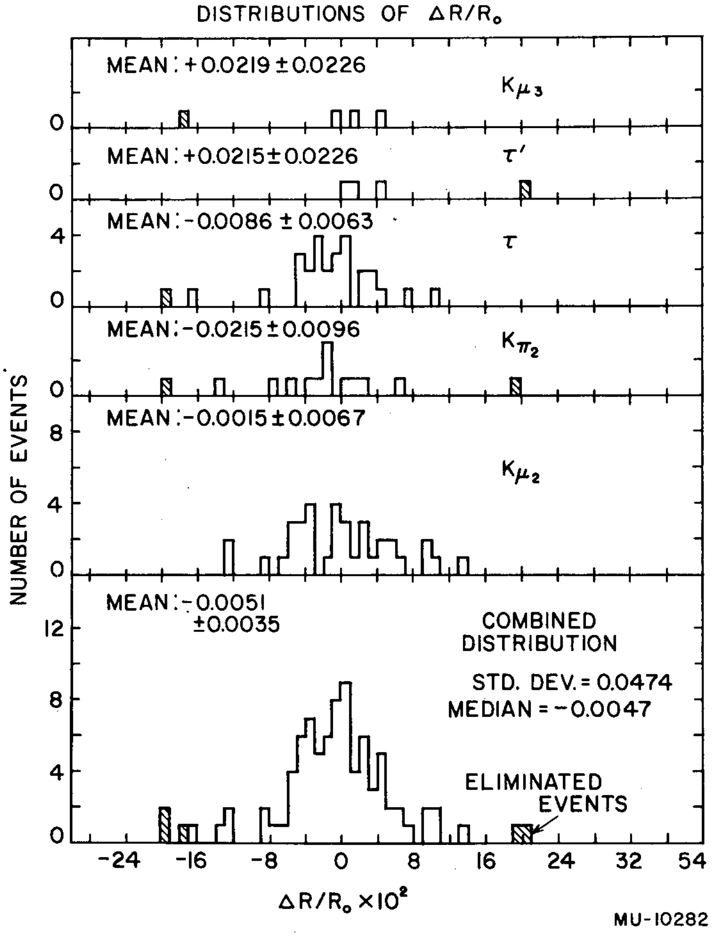

Fig. 3. Histogram of $\frac{\Delta R}{R_O}$ for each type of K particle. Every particle is shown. The five particles indicated by cross-hatching were omitted in the mass calculations.

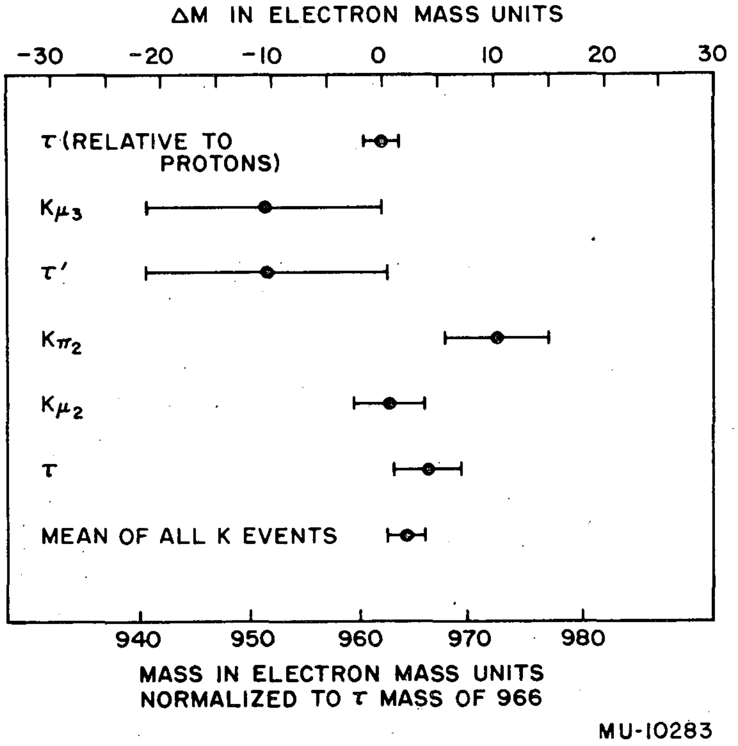

Fig. 4. Mass values for τ , τ ', $K_{\mu 2}$, $K_{\pi 2}$, and $K_{\mu 3}$ mesons. ΔM is the difference in electron mass units as calculated from Eq. (1). For ΔM to be zero, the mean ranges of the particles would coincide with the expected range of a 966-me particle as calculated from the range of the protons and the range-momentum relation. This calculated mass point is denoted in Table I and in the above graph as τ (relative to protons). If we assign an absolute mass of 966 me to the τ meson, the masses of the various K particles are then directly related to the τ meson.