EVIDENCE FOR $K^+ \to \pi^+ + \pi^- + e^+ + \nu$ DECAY MODE*

E. L. Koller, S. Taylor, T. Huetter, and P. Stamer
Department of Physics, Stevens Institute of Technology, Hoboken, New Jersey
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A K^+-meson decay of particular interest has been found during a systematic examination of K^+ endings in 600μ Ilford G-5 nuclear emulsion. The exposure of the emulsions stack, carried out at the Bevatron of the Lawrence Radiation Laboratory, was for the primary purpose of measuring the neutral-pion lifetime by the method of Harris, Orear, and Taylor.[1] About 30 000 K^+ endings have been examined to date. The event of interest appears to be an example of a K^+ meson decaying to two particles of pion or muon mass, one electron, and one or more neutral particles. Analysis of the event indicates that the most likely possibility is $K^+ \to \pi^+ + \pi^- + e^+ + \nu$. Figure 1 shows a camera lucida drawing of the event.

Track 4 has the qualitative appearance of the track of a K^+ meson decaying at rest at point O. Identification as a K is confirmed by grain counting. Grain-count data are summarized in Table I. The range-energy and grain count-energy curves of Barkas and Young have been used throughout.[2]

Tracks 1 and 2 have the qualitative appearance of pion or muon tracks. Track 1 ends in a zero-prong star after a range of 3.5 ± 0.3 mm, and is identified as a pion or muon by grain counting. Track 2 leaves the stack after a range of 13.1 ± 0.7 mm, and appears to be nearly at the end of its range. Grain counting near the point of leaving the stack gives ~ 7 times minimum, or a residual range of ~ 0.2 mm beyond the stack for either a pion or muon. Grain counting near the K decay point then identifies track 2 as either a pion or muon. See Table I for grain-count data and Table II for other data on tracks 1 and 2. No great significance is to be attached to the fact that the grain count for track 1 agrees more closely with the expected grain count for a pion than for a muon, and vice versa for track 2, since past experience indicates considerable difficulty in identifying any one track as a pion or muon by grain counting alone.

Track 3 has the qualitative appearance of an

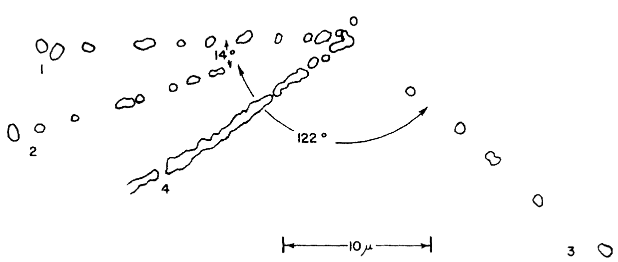

FIG. 1. Camera lucida drawing of the event. Track 4 is the primary, decaying at O. The angles are the projected angles in the plane of the emulsion.

Table II. Data on the secondary tracks. θ is the dip angle measured from the plane of the emulsion, R is the range, $p\beta$ is the product of momentum and velocity, P is the particle identification, and T is the kinetic energy

Track	$\theta°$	R (mm)	$p\beta$ (MeV)	P	T (MeV)
1	-29.0	3.5 ±0.3		π or μ	12.7 ±0.6 11.3 ±0.6
2	-17.5	13.3 ±0.8		π or μ	27.5 ±0.8 24.5 ±0.8
3	28.5		48^{+20}_{-10}	e	47^{+20}_{-10}

Table I. Identification of tracks by grain counting. R_g is the residual range at the grain-count point, G is the grain count relative to minimum, and P is the particle identification. Expected G's for various particles are from the data of reference 2.

Track	R_g (mm)	G	Expected G: μ	π	K	p	P
1	3.0	3.80 ±0.17	3.45	3.80	5.75		μ or π
2	12.4	2.13 ±0.10	2.11	2.30	3.60		μ or π
4	10.4	3.77 ±0.22		2.45	3.80	4.75	K

electron track. It has a grain count near the K ending of 0.97 ± 0.08 times minimum. The track is relatively steep (dip angle 28.5°) and the emulsions have considerable distortion. However, an attempt to carry out multiple scattering measurements gives a $p\beta$ (product of momentum and velocity) of 43 ± 5 MeV, where the error is purely statistical and no corrections have been applied. Applying a correction for systematic deflections in the most distorted plates, a $p\beta$ of 48 ± 7 MeV is obtained. Again the error is statistical only. To check the correction, the multiple scattering of a secondary from a K_l^+ decay (presumed to be either $K_{\pi 2}$ or $K_{\mu 2}$) was measured. This track passed through the same plates as track 3, within a few millimeters of it, and had similar dip and azimuthal angles. Comparing the "apparent" $p\beta$ of this track with the known $p\beta$ of the π and μ from $K_{\pi 2}$ and $K_{\mu 2}$, respectively, the "scattering" due to distortion was estimated and a corrected $p\beta$ of 49 ± 8 MeV obtained for track 3. Again the error is statistical only. This is in agreement with the value obtained by the first method of correction. Considering the problems of the scattering measurements, the $p\beta$ of track 3 is estimated as 48_{-10}^{+20} MeV. For a minimum or plateau grain-count track, only an electron can have this value of $p\beta$. Hence track 3 is identified as an electron. Data on track 3 are given in Table II.

If the event is accepted as a K decay, another argument as to the identity of the tracks 1 and 2 can be made. Pions, muons, and electrons are the only charged particles which can occur as K decay products. Only pions and muons can give heavily ionizing tracks. Hence tracks 1 and 2 are identified as π or μ tracks.

From the geometry of the event (see Fig. 1), it is clear that momentum is not conserved if the visible tracks alone are considered. Hence there must be at least one neutral particle. Considering only four-particle decay modes, the possible decay modes are listed in Table III. For each case, the total energy of the electron has been calculated, considering the charged pion and muon momenta as known and the direction of the electron as known. For those modes involving both a charged pion and muon, two electron energies are obtained, depending on whether track 1 or 2 is taken as the pion track. The errors on the calculated electron energies are about 5%. Mode (a) of Table III is in good agreement with the measured electron total energy of 48_{-10}^{+20} MeV. Considering mode (b), it seems unlikely that the measured electron energy would be this low, since the uncorrected measured value (43 ± 5 MeV) is nearly two statistical standard deviations higher than the calculated value. However, mode (b) cannot be entirely excluded. For mode (c), the calculated electron energy is nearly three standard deviations higher than the corrected measured value. Hence mode (c) seems very unlikely, but in view of the difficulties of the scattering measurements, it cannot be positively excluded. Mode (d) is excluded.

Table III. Calculated electron total energies, E_e, assuming various four-particle decay modes.

Decay mode	E_e (MeV)
(a) $K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu$	52
(b) $K^+ \rightarrow \pi + \mu + e + \pi^0$	26 or 34
(c) $K^+ \rightarrow \pi + \mu + e + \gamma$	104 or 110
(d) $K^+ \rightarrow \mu^+ + \mu^- + e^+ + \nu$	139

If one invokes the rule of separate conservation of μ-type and electron-type leptons,[3] decay modes (a) and (d) would be permitted, but modes (b) and (c) would be ruled out. As further evidence against modes (b) and (c), consider $K^+ \rightarrow \pi + \mu + e$. This mode has never been observed, although in general it would be expected to be more frequent than modes (b) and (c).

Certain other tentative explanations of the event have been considered but rejected: (a) The event cannot be a stray K^- star, as strangeness could not be conserved without violating conservation of energy. (b) It cannot be a τ^+ decay with a very short ($\sim 1\ \mu$) π decaying either at rest or in flight into an electron plus neutrino, as energy and momentum would not be conserved for the π. One cannot, of course, rule out the accidental association of the tracks in the emulsion. However, it would be necessary to invoke the accidental presence of two extra tracks. Nor can the possibility of two or more neutral decay particles be ruled out.

Chadan and Oneda[4] have calculated the probability of $K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu$ relative to τ^+ or K_{e3}^+ as approximately 10^{-2} to 10^{-3}. They have also calculated the energy spectrum of the e^+ or ν, showing a broad maximum at about 70 MeV. Mathur[5] has calculated the probability of $K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu$ relative to K_{e3}^+, obtaining about 2.5×10^{-3} and 2.5×10^{-4} by different methods, and regarding the latter figure as having greater uncertainty. Chadan and Oneda[6] and Ciocchetti[7] have considered the degree to which the probability for $K^+ \to \pi^+ + \pi^- + e^+ + \nu$ would be enhanced by final-state pion-pion interactions. Since a total of (2 or 3) $\times 10^3$ τ^+ events have been examined by various observers to date with varying degrees of analysis, the experimental observation of a single $K^+ \to \pi^+ + \pi^- + e^+ + \nu$ is in reasonable agreement with the above theoretical predictions.

In our opinion, the observed event is most likely $K^+ \to \pi^+ + \pi^- + e^+ + \nu$. Behrends and Sirlin[8] have suggested looking for the decay mode $K^+ \to \pi^+ + \pi^+ + e^- + \tilde{\nu}$ as an unambiguous violation of the $\Delta S = \Delta Q$ rule. The present event is in agreement with the rule.

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[1]G. Harris, J. Orear, and S. Taylor, Phys. Rev. 106, 327 (1957).

[2]W. H. Barkas and D. M. Young, University of California Radiation Laboratory Report UCRL-2759 Rev. (unpublished).

[3]See G. Danby et al., Phys. Rev. Letters 9, 36 (1962) for experimental verification of the existence of two kinds of neutrinos and also for numerous references to theoretical papers on the two-neutrino hypothesis.

[4]K. Chadan and S. Oneda, Phys. Rev. Letters 3, 292 (1959).

[5]V. S. Mathur, Nuovo cimento 14, 1322 (1959).

[6]K. Chadan and S. Oneda, Phys. Rev. 119, 1126 (1960).

[7]G. Ciocchetti, Nuovo cimento 25, 385 (1962).

[8]R. E. Behrends and A. Sirlin, Phys. Rev. Letters 8, 221 (1962).

ON THE SPIN OF THE K^* RESONANCE†

William Chinowsky, Gerson Goldhaber, Sulamith Goldhaber, Wonyong Lee,‡ and Thomas O'Halloran
Physics Department and Lawrence Radiation Laboratory, University of California, Berkeley, California
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The production of the K^* resonance[1] in the reaction[2] $K^+ + p \to K^* + N_{33}^*$ at 1.96 BeV/c has permitted us to identify the K^* as a vector meson. Following a method due to Adair,[3] we examined the distribution in the angle α between the outgoing K^+ meson in the K^* c.m. system and the incident K^+ direction. We find a strong anisotropy which can be fitted with $\cos^2\alpha$, and hence conclude that the spin[4,5] of the K^* is ≥ 1. Alston et al. presented evidence for the K^* spin to be less than two within three standard deviations.[1] This result, combined with the present data, allows us to assign spin one to the K^*.[6] It thus follows that the KK^* relative parity is even. For odd $K\Lambda N$ parity[7] this leads to the spin and parity assignment 1^- for the K^*.

The experiment was carried out with the 20-inch Brookhaven bubble chamber[8] in a separated beam[9] tuned to K^+ mesons.

The reaction we have studied is

$$K^+ + p \to K^+ + \pi^- + p + \pi^+. \qquad (1)$$

This reaction, which amounts to about 10% of the total cross section, has the property that a large proportion of events occur in the double resonant state

$$K^+ + p \to K^{*0} + N_{33}^{*++}, \quad K^{*0} \to K^+ + \pi^-, \quad N_{33}^{*++} \to p + \pi^+. \qquad (2)$$

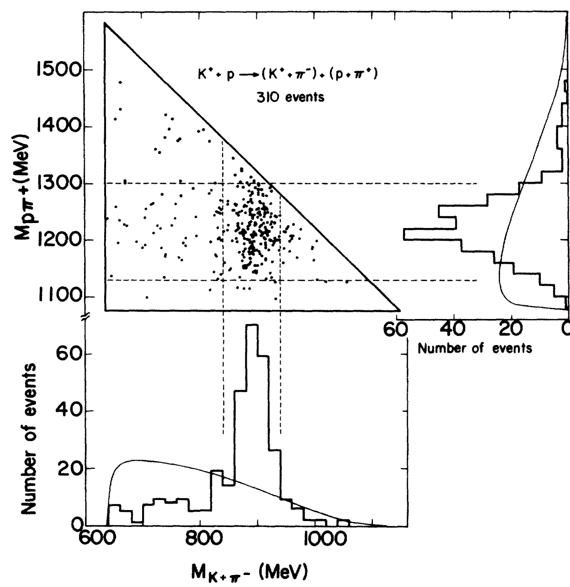

FIG. 1. Scatter diagram of the effective-mass distribution $M_{p\pi^+}$ versus $M_{K^+\pi^-}$. The triangle delineates the kinematical limits. The projections on the $M_{p\pi^+}$ mass axis show the N_{33}^* production, while the projection on the $M_{K^+\pi^-}$ axis shows the simultaneous K^* production. The curves give the distributions expected from phase-space calculations without dynamic effects.

The evidence for Reaction (2) is shown in Fig. 1, where we present a plot of the effective mass distribution $M_{p\pi^+}$ against $M_{K^+\pi^-}$. The triangle