SEARCH FOR DOUBLY-CHARGED WEAK CURRENTS

THROUGH $K^+ \rightarrow \pi^- e^+ \mu^+$

E. W. Beier, D. A. Buchholz,
A. K. Mann and S. H. Parker

Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

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ABSTRACT

Results are presented of a search for the decay mode $K^+ \rightarrow \pi^- e^+ \mu^+$ which requires doubly-charged weak currents for its existence. Limits are also obtained on the branching ratios for the decay modes $K^+ \rightarrow \pi^+ e^+ \mu^-$ and $K^+ \rightarrow \pi^+ e^+ e^-$. A comparison of some present experimental limits on neutral and doubly-charged weak currents is given.

It has been recognized for some time that there are three alternative schemes of assigning lepton numbers and specifying lepton number conservation^{1,2,3} which are consistent with all of the experimental information now available on weak interactions. Leaving aside the so-called "multiplicative" scheme³, which is not immediately relevant here⁴, the two additive schemes differ in that:

- (i) the usual scheme¹ assigns $L_\mu = +1$ to μ^- and ν_μ , $L_\mu = -1$ to μ^+ and $\bar{\nu}_\mu$, $L_e = +1$ to e^- and ν_e , $L_e = -1$ to e^+ and $\bar{\nu}_e$ and assumes both $\sum_j L_{uj}$ and $\sum_j L_{ej}$ to be separately conserved; whereas

(ii) the alternative scheme² assigns $L = +1$ to e^- , μ^+ and ν ; $L = -1$ to e^+ , μ^- and $\bar{\nu}$ and assumes only $\sum_j L_j$ to be conserved. This assignment of lepton numbers in conjunction with experimental information on the helicities of neutrinos and antineutrinos results in identifying $L = +1$ with ν_e and $\bar{\nu}_\mu$ and $L = -1$ with ν_μ and $\bar{\nu}_e$.

The two schemes have almost all predictions in common providing that invariance under neutrino-chirality, i.e., under the transformation $\psi \rightarrow \gamma_5 \psi$, is included in any formulation⁵ employing scheme (ii). For example, the processes $K_L^0 \rightarrow \mu^+ \mu^-$, $K^+ \rightarrow \pi^+ e^+ e^-$, $K^+ \rightarrow \pi^+ \nu_\mu \bar{\nu}_\mu$, etc., involving either first-order weak neutral currents or higher order weak interactions, do not violate lepton number conservation in either scheme⁶. Similarly, the decays $\mu^+ \rightarrow e^+ + \gamma$, $K^+ \rightarrow \pi^+ e^\pm \mu^\mp$, $K^+ \rightarrow \pi^+ \nu_\mu \nu_\mu$, etc. are forbidden in both schemes by lepton number conservation.

It is of interest, however, that the strangeness conserving reactions $\nu_\mu + (Z,A) \rightarrow e^+ + (Z-1,A)$ and $\mu^- + (Z,A) \rightarrow e^+ + (Z-2,A)$ and the strangeness-changing decay $K^+ \rightarrow \pi^- e^+ \mu^+$ are forbidden in scheme (i) but are allowed in scheme (ii) by lepton number conservation. The reaction $\nu_\nu + (Z,A) \rightarrow e^+ + (Z-1,A)$ is forbidden or at least inhibited relative to, say, $\bar{\nu}_e + (Z,A) \rightarrow e^+ + (Z-1,A)$ by the conservation of neutrino-chirality alone. The reaction $\mu^- + (Z,A) \rightarrow e^+ + (Z-2,A)$ and the decay $K^+ \rightarrow \pi^- e^+ \mu^+$ require either a primitive doubly-charged weak current⁷ or higher order weak interactions for their existence. The experimentally observed inhibition of the latter reactions may be due to a chirality conservation principle similar to neutrino-chirality conservation which manifests itself in part through the value of G_2 , the weak coupling constant associated with doubly-charged weak currents, relative to the value of G , the usual weak coupling constant⁵.

To the extent therefore that the two lepton number schemes are at present equivalent it is particularly meaningful to search for the processes allowed by total lepton number conservation in scheme (ii) and not explicitly forbidden by neutrino-chirality invariance⁸. Observation of one or both of those processes would constitute unequivocal evidence in favor of scheme (ii) and for the existence of doubly-charged weak currents. Failure to observe either process leaves unresolved the question of lepton number assignment but does provide limits on the $\Delta S = 0$ and $\Delta S = 1$ doubly-charged weak amplitudes.

We report here the result of a search for the decay mode $K^+ \rightarrow \pi^- e^+ \mu^+$, and also for the modes $K^+ \rightarrow \pi^+ e^+ \mu^-$ and $K^+ \rightarrow \pi^+ e^+ e^-$. The experimental arrangement has been described previously⁹. Briefly, a partially separated charged kaon beam of momentum 1.8 GeV/c was produced at 10⁹ from the G-10 target of the Brookhaven National Laboratory AGS. The incident kaons were electronically tagged by a beam Cerenkov and scintillation counters and their momenta measured to $\Delta p/p \approx \pm 1\%$ in a simple beam spectrometer. Acceptable kaon decays occurred in the first half of a wide gap optical spark chamber 36" long located in a magnet with a central field of about 6 kilogauss. Directly downstream from the spark chamber was a four-counter hodoscope to indicate that a decay with more than one charged particle occurred in the spark chamber. Behind this front hodoscope were two large volume, optically segmented, focusing threshold Cerenkov counters, CI (8 segments) and CII (16 segments); these distinguished electrons from pions and also allowed events with two electrons to be distinguished from events with one electron among the decay products. A 16-element rear hodoscope was used in conjunction with the Cerenkov counters to identify events with three or more charged particles, of which one and only one was an electron.

During the experiment 3×10^{10} charged kaons entered the detector, giving rise to 1.2×10^9 K decays. The particle selection criteria mentioned above resulted in 3×10^5 spark chamber photographs yielding 2.4×10^4 three-prong decays within the fiducial volume. The sample of events reported here is about 3/4 of the total. Each three-prong event was tested for a fit to the $K \rightarrow \pi e \mu$, $K \rightarrow \pi e e$, $K \rightarrow \pi \pi \gamma$, K_{e4} , $K_{\pi 2}$ and τ hypotheses¹⁰ by the kinematic fitting program SQUAW. All of the accepted events satisfy a loose Chi-squared criterion and events with only one electron satisfy the requirement that the particle types and trajectories in a given event are properly correlated with the counters and counter segments that in fact triggered the event.

The measured efficiencies of detection of the various kaon decay modes and the numbers of observed events of each type are given in columns 6 and 7 of Table I. The Table shows that the number of K_{e4} events is large and the K_{e4} decay mode with its low branching ratio is clearly distinguished in this experiment from the more abundant decay modes $K_{\pi 2}$ and tau. The Cerenkov counter efficiency for the decay modes $K \rightarrow \pi e \mu$ is the same as that for the K_{e4} and therefore the branching ratio limits for $K \rightarrow \pi e \mu$ are obtained by direct comparison with K_{e4} . The Cerenkov counter efficiency for the decay mode $K \rightarrow \pi^+ e^+ e^-$ is essentially similar to that for $K^+ \rightarrow \pi^+ \pi^0$ with $\pi^0 \rightarrow e^+ e^- \gamma$ so that the branching ratio limit on $K \rightarrow \pi^+ e^+ e^-$ is obtained by comparison with the $K_{\pi 2}$ decay mode and is consequently restricted in sensitivity by the small number of $K_{\pi 2}$ events observed here.

In the search for $K \rightarrow \pi e \mu$ and $K \rightarrow \pi e e$ the backgrounds from taus, K_{e4} and $K_{\pi 2}$ are severely restricted by kinematics. Fig. 1 shows in (a) the measured deviations from coplanarity of tau events and in (b) the invariant mass M_X calculated from $K \rightarrow \pi \pi X$ for tau events. With the resolution shown in (b) no taus are able to simulate $K \rightarrow \pi e \mu$ in which the equivalent $M_X = 0.5$ MeV. We

show in Fig. 2 the observed invariant mass distribution calculated from (a) $K \rightarrow \pi\pi X$ and (b) $K \rightarrow \pi\mu X$ for K_{e4} events. There are few events in (a) with $M_X \leq 20$ MeV and $p_\nu^{\text{lab}} \leq 40$ MeV/c, which is necessary if a K_{e4} is to simulate $K \rightarrow \pi e\mu$. As shown in Fig. 2b, the distribution in M_X for K_{e4} treated as $K \rightarrow \pi\mu X$ moves even further away from $M_X = 0$. K_{e4} decays are therefore strongly inhibited kinematically from reconstructing as $K \rightarrow \pi e\mu$. The suppression of $K^+ \rightarrow \pi^+ \pi^0$, is largely accomplished by the Cerenkov counters but in addition $K_{\pi 2}$ events are very unlikely to simulate $K \rightarrow \pi e\mu$ because (1) they are not in general coplanar in the kaon center of mass system; and (2) the value $p_\pi^+ = 205$ MeV/c of the pion momentum in the K center of mass which we measure with an accuracy of $\pm 5\%$ is almost at the end of the region allowed kinematically in $K \rightarrow \pi e\mu$.

There is one event that fits the hypothesis $K^+ \rightarrow \pi^- e^+ \mu^+$ and zero events that fit as $K^+ \rightarrow \pi^+ e^+ \mu^-$ with Chi-squared less than 10. For comparison, 78 percent of the observed tau events, which also involve 4-constraint fits, have $\chi^2 < 10$. The lone $K^+ \rightarrow \pi^- e^+ \mu^+$ candidate also fits as a K_{e4} with an acceptable Chi-squared. Furthermore, the vertex of that event occurs within a few centimeters of the downstream limit of the fiducial region in the wide gap spark chamber where the accuracy of reconstruction is poorest. In our opinion this event is a questionable $K \rightarrow \pi^- e^+ \mu^+$ decay; nevertheless, we have retained it as a possible $K^+ \rightarrow \pi^- e^+ \mu^+$ and computed the upper limit to the branching ratio of that mode on that basis.

There are three events that fit as $K^+ \rightarrow \pi^+ e^+ e^-$ with Chi-squareds less than 10. Each of the events fits also as a $K_{\pi 2}$ with appreciably lower Chi-squared. A modest requirement on the dilepton invariant mass, $M_{ee} \geq 40$ MeV, eliminates the three events; 0.9 of all $K_{\pi 2}$ events and 0.04 of all $K \rightarrow \pi ee$ have $M_{ee} \leq 40$ MeV.

The principal results of this experiment are the limits on the branching ratios

$$\frac{\Gamma(K^+ \rightarrow \pi^- e^+ \mu^+)}{\Gamma(K^+)} < 2.8 \times 10^{-8}$$

(90% confidence).

$$\frac{\Gamma(K^+ \rightarrow \pi^+ e^+ \mu^-)}{\Gamma(K^+)} < 1.4 \times 10^{-8}$$

It is perhaps useful also to compare the limits on the amplitudes of neutral and doubly-charged weak currents as is done in Table II. Differences in phase space contained in the individual rates are largely canceled out of the ratios in Table II. The limit obtained from the strangeness conserving muon capture reaction¹¹ can also be compared more directly with the limits from the strangeness changing decays. Each of the ratios involves a ratio of weak hadronic matrix elements multiplied by either G_0/G or G_2/G . Evaluation of weak hadronic matrix elements such as $\langle \pi^- | k_\alpha(x) | \Delta S=1 | K^+ \rangle$ depends sensitively on the model chosen and consequently accurate limits on G_0/G or G_2/G cannot be extracted directly from the limits presented in Table II. It is worth noting that the upper bounds on the relative amplitudes given in Table II are about equal to or less than the observed magnitude of the CP violation in the neutral kaon system and appreciably less than the limits on neutral current amplitudes obtained so far from neutrino-induced semileptonic reactions.¹²

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References and Footnotes

- * Work supported in part by the U. S. Atomic Energy Commission.
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 10. Tau events are observed here because of the probability ($\sim 10^{-4}$) of $\pi^\pm$ charge exchange and subsequent electron production in the material before or in CI. $K_{\pi 2}$ events arise through the chain: $K^\pm \rightarrow \pi^\pm \pi^0$, $\pi^0 \rightarrow e^+ e^- \gamma$, in which only one of the Dalitz pair electrons is counted in CI and CII. Other decay modes, i.e., $K_{\mu 3}$, $K_{e 3}$ and $\tau^\pm (\pi^\pm \pi^0 \pi^0)$, that are also detected

through π^0 decay into $e^+e^-\gamma$, are kinematically suppressed. $K \rightarrow \pi ee$ events, like $K_{\pi 2}$, are detected through Cerenkov counter inefficiency and radiative taus ($K \rightarrow \pi\pi\pi\gamma$) are triggered by photon conversion.

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Table I. Detection Efficiencies and Results of the Experiment

Decay Mode	Q	Con- straints	Efficiency of Detection			Observed Events	Branching Ratio
	Mev		Hodoscope (Geometrical)	Cerenkov Counter	Total		
K_{e4}	214	1	0.22	0.98 ^c	0.215	7330 ^h	$(3.7 \pm 0.2) \times 10^{-5f}$
tau	75	4	0.55	1.8×10^{-4c}	1.0×10^{-4}	5745 ^e	0.555 ^f
$K_{\pi 2}$	219	2	0.065	6.3×10^{-4}	0.46×10^{-6d}	111	0.21 ^f
$K \rightarrow \pi e e$	353	4	0.14 ^b	6.3×10^{-4}	0.88×10^{-4}	0	$< 3.2 \times 10^{-5g}$
$K^+ \rightarrow \pi^- e^+ \mu^+ a$	249	4	0.18 ^b	0.98	0.176	1	$< 2.8 \times 10^{-8g}$
$K^+ \rightarrow \pi^+ e^+ \mu^- a$	249	4	0.20 ^b	0.98	0.196	0	$< 1.4 \times 10^{-8g}$

^aThe experiment actually utilized approximately equal numbers of K^+ and K^- decays but for simplicity we refer to them all as K^+ decays here.

^bCalculated from phase space.

^cMeasured in an independent experiment.

^dIncludes a factor of $\sim 1/80$ for the probability of $\pi^0 \rightarrow e^+ e^- \gamma$.

^eNone of these tau decays reconstructs as a $K \rightarrow \pi e \mu$ or $K \rightarrow \pi e e$ and therefore none have been tested for consistency of electron trigger. Taus do reconstruct as K_{e4} in which case the test of trigger consistency is applied and rejects a large fraction of taus. This accounts for the difference of tau events reported here and in reference 9.

^fFrom Review of Particle Properties, Physics Letters 39B, 1 (1972).

^g90% confidence level using Poisson statistics.

^hWhen compensation is made for the kinematic criteria which define the K_{e4} sample the number becomes 8060.

Table II. Comparison of experimental upper limits on weak neutral and doubly-charged amplitudes for processes that do not violate lepton number conservation in at least one of the assignment schemes.

Type	Decay Mode	Ref.	Limit
Neutral	$\left[\frac{\Gamma (K^+ \rightarrow \pi^+ e^+ e^-)}{\Gamma (K^+ \rightarrow \pi^0 e^+ \nu_e)} \right]^{\frac{1}{2}}$	(a)	$< 3.0 \times 10^{-3}$
	$\left[\frac{\Gamma (K^+ \rightarrow \pi^+ \nu_\mu \bar{\nu}_\mu)}{\Gamma (K^+ \rightarrow \pi^0 e^+ \nu_e)} \right]^{\frac{1}{2}}$	(b)	$< 5.0 \times 10^{-3}$
	$\left[\frac{\Gamma (K_L^0 \rightarrow \mu^+ \mu^-)}{\Gamma (K^+ \rightarrow \mu^+ \nu_\mu)} \right]^{\frac{1}{2}}$	(b)	$< 5.3 \times 10^{-3}$
Doubly-charged	$\left[\frac{\Gamma (K^+ \rightarrow \pi^- e^+ \mu^+)}{\Gamma (K^+ \rightarrow \pi^0 \nu_\mu \mu^+)} \right]^{\frac{1}{2}}$	(c)	$< 9.4 \times 10^{-4}$
	$\left[\frac{\sigma(\mu^- + Cu \rightarrow e^+ + Co)}{\sigma(\mu^- + Cu \rightarrow \nu_\mu + Ni)} \right]^{\frac{1}{2}}$	(d)	$< 1.6 \times 10^{-4}$

^aD. B. Clarke, et al., Bull. Am. Phys. Soc. 17, 493 (1972).

^bSee footnote f in Table I.

^cThis experiment.

^dReference 11.

Figure Captions

Fig. 1. (a) Distribution of deviations from coplanarity measured in tau events.

(b) Invariant mass distribution of X obtained by reconstructing observed tau events as $K \rightarrow \pi\pi X$.

Fig. 2. Invariant mass distributions of X obtained by reconstructing observed K_{e4} events as (a) $K \rightarrow \pi\pi X$ and (b) $K \rightarrow \pi\mu X$.

TAU EVENTS

$\sigma = 3.6^\circ$

$M_X = 139.5 \pm 7.4 \text{ MeV}$

Figure 1.

7330 $K \rightarrow \pi\pi e\nu$ DECAYS
TREATED AS $K \rightarrow \pi\pi X$

INVARIANT MASS IN MeV

7330 $K \rightarrow \pi\pi e\nu$ DECAYS
TREATED AS $K \rightarrow \pi\mu X$

INVARIANT MASS IN MeV

Figure 2.