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PHYSICAL REVIEW D VOLUME 8, NUMBER 11 1 DECEMBER 1973

Search for Rare K^+ Decays. II. $K^+ \to \pi^+ \nu\bar{\nu}$ *†

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(Received 2 July 1973)

In a counter experiment at the Lawrence Berkeley Laboratory Bevatron we have searched for the process $K^+ \to \pi^+\nu\bar{\nu}$ in the kinetic energy interval $60 < T_\pi < 105$ MeV and have found no examples of this decay mode. Combining our data with those of Klems, Hildebrand, and Stiening for the interval $117 < T_\pi < 127$ MeV, we obtain the limit $\Gamma(K^+ \to \pi^+\nu\bar{\nu}) < 5.6\times10^{-7}\ \Gamma(K^+ \to \text{all})$, assuming a (vector) pion spectrum like that for $K^+ \to \pi^0 e^+\nu$. Limits are presented for other assumed spectra.

I. INTRODUCTION

Klems, Hildebrand, and Stiening[1] have reported a search for the process

$$K^+ \to \pi^+ \nu\bar{\nu} \tag{1}$$

using apparatus sensitive to π^+ near the kinematic limit ($T_{\pi^+} = 127$ MeV). We report here an extension of the search to the region $60 < T_{\pi^+} < 105$ MeV. Neither experiment has given evidence for this decay mode. Both may be used to establish a limit for the branching ratio.

Both experiments have used the stopping K^+ beam of the LBL Bevatron, and in both counter techniques have been used to identify $K^+ \to \pi^+ \to \mu^+ \to e^+$ decays, measure the π^+ range, and exclude events with other charged particles or γ rays.

In the second experiment a lead-glass γ detector completely surrounded the kaon stopper. This arrangement allowed us to look for examples of process (1) at pion energies below that for

$$K^+ \to \pi^+ \pi^0 \tag{2}$$

($T_{\pi^+} = 108$ MeV) without errors due to simulation of (1) by (2) when the π^+ range and the π^+-π^0 angle were reduced by scattering. The new apparatus and its calibration are described in our report on a concurrent experiment on $K^+ \to \mu^+ \nu\bar{\nu}\nu$.[2]

TABLE I. Experimental limits on reactions involving leptonic neutral currents.[a]

Reaction	Branching ratio[b]	Reference
$K^+\to\pi^+\nu\bar\nu$	$<1.4\times10^{-6}$	1[c]
	$<5.7\times10^{-5}$	3[c]
	$<5.6\times10^{-7}$	this work[c,d]
$K^+\to\mu^+\nu\bar\nu\nu$	$<6.0\times10^{-6}$	2[e]
$K^+\to\pi^+e^+e^-$	$<3.5\times10^{-7}$	4[f]
$K^+\to\pi^+\mu^+\mu^-$	$<2.4\times10^{-6}$	5
$K^+\to\pi^+\pi^0e^+e^-$	$<8.0\times10^{-6}$	6
$K_L^0\to\pi^+\pi^-e^+e^-$	$<3.0\times10^{-5}$	7
$K_L^0\to e^+e^-$	$<1.8\times10^{-9}$	8
$K_L^0\to\mu^+\mu^-$	$<2.4\times10^{-9}$	9
	$(11^{+10}_{-5})\times10^{-9}$	10
$K_S^0\to\mu^+\mu^-$	$<3.1\times10^{-7}$	11
$\nu_\mu e^-\to\nu_\mu e^-$	$<0.44\ \sigma_{V-A}(\nu_e e^-\to\nu_e e^-)$	12
$\bar\nu_\mu e^-\to\bar\nu_\mu e^-$	$<0.62\ \sigma_{V-A}(\nu_e e^-\to\nu_e e^-)$	12
	$<2.1\ \ \sigma_{V-A}(\bar\nu_e e^-\to\bar\nu_e e^-)$	12
$\nu_e e^-\to\nu_e e^-$	$<40\ \ \sigma_{V-A}(\nu_e e^-\to\nu_e e^-)$	13
$\bar\nu_e e^-\to\bar\nu_e e^-$	$<4\ \ \sigma_{V-A}(\bar\nu_e e^-\to\bar\nu_e e^-)$	14
	$<3.0\ \ \sigma_{V-A}(\bar\nu_e e^-\to\bar\nu_e e^-)$	15
$\nu_\mu p\to\nu_\mu p$	$<0.22\ \sigma(\nu_\mu n\to\mu^-p)$	16
$\nu_\mu N\to\nu_\mu N\pi^0$	$<0.14\ \sigma(\nu_\mu n\to\mu^-p\pi^0)$	17[g]
$\nu_\mu p\to\nu_\mu\Delta^+$	$<0.46\ \sigma(\nu_\mu p\to\mu^-\Delta^{++})$	16
	$<0.31\ \sigma(\nu_\mu p\to\mu^-\Delta^{++})$	12
$\bar\nu_e d\to\bar\nu_e np$	$<60\ \ \sigma(\bar\nu_e d\to nne^+)$	18[h]

[a]For earlier results, see Ref. 1.

[b]Branching ratios relative to all decay modes. All figures at the 90% confidence level except as noted.

[c]Calculated for a pion spectrum like that from $K^+\to\pi^0e^+\nu$.

[d]See text Sec. III and Table II.

[e]Calculated for the muon spectrum proposed by Bardin, Bilenky, and Pontecorvo (see second paper of Ref. 2).

[f]Preliminary result.

[g]Perkins (Ref. 12) argues that the limit may be as high as $0.25\sigma(\nu_\mu n\to\mu^-p\pi^0)$ when corrected for charge-exchange effects.

[h]The authors do not state the confidence level. We infer it to be 63%.

Combining our results with those of Klems *et al.*,[1] the upper limits on the branching ratio $\Gamma(K^+\to\pi^+\nu\bar\nu)/\Gamma(K^+\to\text{all})$ corresponding to the three first-order current-current interactions with constant form factors are 1.1×10^{-6} (scalar), 5.6×10^{-7} (vector), and 7.1×10^{-7} (tensor) at the 90% confidence level.

The decay $K^+\to\pi^+\nu\bar\nu$ provides an opportunity to study neutral currents. It can occur in lowest order only by the coupling of neutral hadronic and leptonic currents. If, as our result and the results of other experiments[1-11] indicate (see Table I[1-18]), such lowest-order neutral current couplings are strongly suppressed, the process can also be used to study higher-order weak-interaction effects.

II. EXPERIMENT

The apparatus and experimental technique have been described in Paper I.[2] We shall assume familiarity with Sec. III of that paper and shall add here only a few details which are unique to the search for $K^+\to\pi^+\nu\bar\nu$.

As in the experiment on $K^+\to\mu^+\nu\bar\nu\nu$ we searched for K^+ decays yielding single-charged particles of known range unaccompanied by γ's. Because of the more distinctive signal given by stopping π's ($\pi^+\to\mu^+\to e^+$ instead of $\mu^+\to e^+$) the potential sources of background were much reduced.

Figure 1 shows a distribution of μ^+ pulse heights from $\pi^+\to\mu^+\to e^+$ decays where the π's were produced by $K^+\to\pi^+\pi^0$. It is clear that a μ^+ pulse-height criterion could have been applied to all π-decay data, but since there appeared to be no difficulty with particle identification no μ^+ pulse-height cuts were applied in either the $\pi^+\nu\bar\nu$ search or the $\pi^+\pi^0$ calibration.

The experiment differed from the earlier $K^+\to\pi^+\nu\bar\nu$ search of Klems, Hildebrand, and Stiening[1] in two significant aspects: (i) The new γ detector completely surrounded the K^+ decay region (the "stopper") instead of covering only the hemisphere opposite the π^+ detector, and (ii) the energy interval examined was $60< T_{\pi^+}< 105$ MeV instead of $117< T_{\pi^+}< 127$ MeV (see Fig. 2). These changes reduced the background and allowed a more sensitive search for spectra which are not peaked at the kinematic limit (127 MeV).

III. RESULTS

A. Branching-Ratio Limits for Specific Models

Among 1.14×10^9 K^+ decays, we observed no examples of $K^+\to\pi^+\nu\bar\nu$; among 8.72×10^5 decays, we observed 1627 examples of $K^+\to\pi^+\pi^0$. In order to obtain the branching ratio $\Gamma(K^+\to\pi^+\nu\bar\nu)/\Gamma(K^+\to\pi^+\pi^0)$ from these figures, we must take into account the π^+ absorption in the degraders used for $\pi^+\nu\bar\nu$ and $\pi^+\pi^0$, and we must calculate the effective detection efficiencies $\epsilon_{\pi^+\nu\bar\nu}$ and $\epsilon_{\pi^+\pi^0}$ (ϵ = overlap of assumed spectrum with the appropriate geometric efficiency curve—see Fig. 2).

In Table II we present the branching-ratio limits to be inferred from our data for various models of the decay process. We have taken the 90% confidence limit to be the branching ratio we would compute had we found 2.3 events. The values appearing in the table have been calculated using the relationship

$$\frac{\Gamma(K^+\to\pi^+\nu\bar\nu)}{\Gamma(K^+\to\pi^+\pi^0)}=\frac{(\pi^+\nu\bar\nu/K^+)}{(\pi^+\pi^0/K^+)}\ \frac{T_{\pi^+\pi^0}}{T_{\pi^+\nu\bar\nu}}\ \frac{\epsilon_{\pi^+\pi^0}}{\epsilon_{\pi^+\nu\bar\nu}}\ ,\quad(3)$$

where $(\pi^+\nu\bar\nu/K^+)=2.99\times10^{-9}$ is the number of $\pi^+\nu\bar\nu$

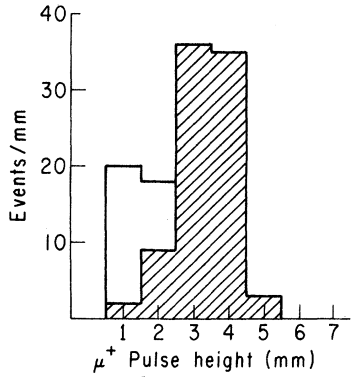

FIG. 1. Distribution of μ^+ pulse heights from 112 $\pi^+ \to \mu^+$ decay events (π^+ from $K^+ \to \pi^+\pi^0$). All events in the sample were judged by the scanner to have clearly resolved π^+ and μ^+ pulses. The shaded area shows events from the same sample for which the leading edge of the μ^+ pulse appeared > 12 mm (> 18 nsec) after the leading edge of the π^+ pulse.

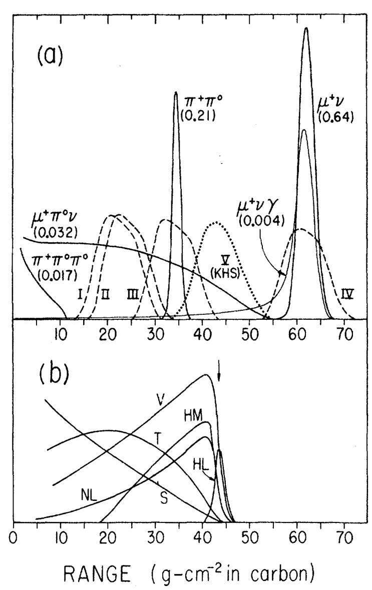

FIG. 2. Range spectra, including straggling and multiple scattering, and geometric efficiency curves. (a) Range spectra for known decays of the type $K^+ \to (\pi^+$ or $\mu^+)$ +neutrals. Vertical scales are arbitrary and are different for the various curves. Branching ratios are shown in brackets. The branching ratio shown for $K^+ \to \mu^+\nu\gamma$ is that calculated using the Cabibbo spectrum with a cutoff $E_\gamma > 10$ MeV. Dashed curves show the geometric detection efficiency vs. range for the degrader configurations used to detect $K^+ \to \pi^+\nu\bar{\nu}$ and $K^+ \to \pi^0\mu^+\nu$ (I and II), $K^+ \to \pi^+\pi^0$ (III), and $K^+ \to \mu^+\nu$ (IV). The dotted curve (V) is the efficiency for the earlier $K^+ \to \pi^+\nu\bar{\nu}$ search (Ref. 1). (b) Range spectra expected for $K^+ \to \pi^+\nu\bar{\nu}$ assuming scalar (S), vector (V), tensor (T), nonlocal (NL), heavy muon (HM), and heavy lepton (HL) models (see Sec. III A and Table II).

events divided by the corresponding number of K^+ signals (assuming 2.3 events and including the chance-rate correction factor, 1.48, discussed in Paper I[2]); $(\pi^+\pi^0/K^+) = (1.89 \pm 0.05) \times 10^{-3}$ is the corresponding ratio for $\pi^+\pi^0$ events (identical selection criteria were applied to $\pi^+\nu\bar{\nu}$ and $\pi^+\pi^0$ events); $T_{\pi^+\pi^0}/T_{\pi^+\nu\bar{\nu}} = 0.80 \pm 0.01$ is the correction for π^+ absorption; and $\epsilon_{\pi^+\pi^0} = 0.0205$ and $\epsilon_{\pi^+\nu\bar{\nu}}$ are the effective detection efficiencies for $K^+ \to \pi^+\pi^0$ [using curve III, Fig. 2(a)] and $K^+ \to \pi^+\nu\bar{\nu}$ [using a weighted average of curves I and II, Fig. 2(a)]. For the spectra shown in Fig. 2(b), the values of $\epsilon_{\pi^+\nu\bar{\nu}}$ are 4.73×10^{-3} (scalar), 5.74×10^{-3} (vector), 7.05×10^{-3} (tensor), 4.88×10^{-3} (nonlocal), 4.15×10^{-3} (heavy muon, $m_L = 430$ MeV), and 9.05×10^{-5} (heavy lepton, $m_L \approx m_K$).

Combining our data with those of Klems, Hildebrand, and Stiening[1] and treating the two experiments as measurements of two energy bins within a single investigation, we are able to establish limits which are lower than for either search alone and are not strongly dependent on the assumed shape of the π^+ spectrum. These limits are shown in the last row of Table II.

B. Prescription for Calculating Limit Corresponding to Any Given π^+ Spectrum

For theories which predict the occurrence of $K^+ \to \pi^+\nu\bar{\nu}$ as a nonlocal or higher-order weak process, or for first-order theories with rapidly varying form factors, the π^+ energy spectrum may differ considerably from those in Table II. We therefore present the following prescription for obtaining the upper limit to be inferred from our result for any given spectrum.

(i) Normalize the assumed π^+ spectrum $F(T)$ such that

$$\int_0^{T_{max}} F(T)dT = 1\,, \tag{4}$$

where T_{max} is the kinematic limit of π^+ kinetic energy (127 MeV).

(ii) Compute the overlap,

$$\Omega = \int P(T)F(T)\,dT\,, \tag{5}$$

of $F(T)$ with the prescription curve $P(T)$ (Fig. 3). The curve $P(T)$ has been prepared for the combined data of this experiment and that of Klems *et al.*[1] taking into account range straggling, multiple scattering, and the range-selection criteria of both experiments.

(iii) Find the branching-ratio limit (90% confidence) using the expression

$$\frac{\Gamma(K^+ \to \pi^+\nu\bar{\nu})}{\Gamma(K^+ \to \pi^+\pi^0)} < 1.9 \times 10^{-6}/\Omega\,, \tag{6a}$$

TABLE II. 90% confidence level upper limits on the branching ratio $\Gamma(K^+\to\pi^+\nu\bar\nu)/\Gamma(K^+\to\text{all})$ for several assumed π^+ spectra.

Spectrum[a]	Scalar $p_\pi(T_{max}-T_\pi)$	Vector[b] p_π^3	Tensor $p_\pi^3(T_{max}-T_\pi)$	Nonlocal[c] p_π^5	Heavy muon[d] ($m_L=430$ MeV) $T_\pi-T_{min}$	Heavy lepton ($m_L=m_K-\delta$; $\delta\to 0$) $\delta(T_{max})$
Ljung and Cline[e]	$<2.3\times10^{-5}$	$<5.7\times10^{-5}$	$<3.1\times10^{-5}$	...	...	...
Klems, Hildebrand, and Stiening[f]	$<2.6\times10^{-5}$	$<1.4\times10^{-6}$	$<1.0\times10^{-5}$	$<1.0\times10^{-6}$ [g]	$<8.5\times10^{-7}$ [g]	$<2.7\times10^{-7}$ [g,h]
This experiment	$<1.1\times10^{-6}$	$<9.4\times10^{-7}$	$<7.7\times10^{-7}$	$<1.1\times10^{-6}$	$<1.3\times10^{-6}$	$<6.0\times10^{-5}$
Combined result[i]						
$\frac{\Gamma(K^+\to\pi^+\nu\bar\nu)}{\Gamma(K^+\to\pi^0e^+\nu)}$	$<2.2\times10^{-5}$	$<1.2\times10^{-5}$	$<1.5\times10^{-5}$	$<1.1\times10^{-5}$	$<1.1\times10^{-5}$	$<5.5\times10^{-6}$
$\frac{\Gamma(K^+\to\pi^+\nu\bar\nu)}{\Gamma(K^+\to\text{all})}$	$<1.1\times10^{-6}$	$<5.6\times10^{-7}$	$<7.1\times10^{-7}$	$<5.2\times10^{-7}$	$<5.2\times10^{-7}$	$<2.7\times10^{-7}$

[a] $T_{max}=127$ MeV. $T_{min}=74$ MeV.
[b] Pion spectrum like that from $K^+\to\pi^0e^+\nu$.
[c] Spectrum given by Singh and Wolfenstein (Ref. 21).
[d] See Sec. IV and Refs. 22 and 23.
[e] Ref. 3.
[f] Ref. 1.
[g] Inferred by the present authors using the data of Ref. 1.
[h] This differs slightly from the limit ($<2\times10^{-7}$) inferred by Singh and Wolfenstein (Ref. 21); we were able to work from original information on the earlier experiment.
[i] From the combined data of this experiment and Ref. 1.

or

$$\frac{\Gamma(K^+\to\pi^+\nu\bar\nu)}{\Gamma(K^+\to\text{all})}<3.9\times10^{-7}/\Omega\ . \qquad (6b)$$

IV. DISCUSSION

Klems, Hildebrand, and Stiening[1] have discussed the class of reactions represented by $K^+\to\pi^+\nu\bar\nu$, reactions which should occur if neutral hadronic and leptonic currents simultaneously participate in weak interactions. The absence of such reactions, as indicated by our results and the others listed in Table I, can be understood within the current-current interaction theory in any of four ways: (i) Neutral leptonic currents are forbidden; (ii) neutral hadronic currents are forbidden; (iii) all neutral currents are forbidden; or (iv) hadronic and leptonic neutral currents exist but do not couple in the weak interactions. Since it appears that neutral hadronic currents must be included in the weak Hamiltonian in order to account for the empirical $|\Delta I|=\frac{1}{2}$ rule of strangeness-changing decays,[19] the first and last possibilities would seem to be more attractive. If hadronic neutral currents do not exist, the $|\Delta I|=\frac{1}{2}$ rule must be considered a dynamic effect caused by the strong interactions rather than a basic property of the weak interaction. In this case, it appears that each decay which obeys this rule would require a separate explanation.

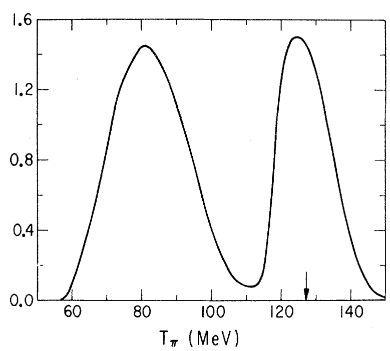

FIG. 3. Prescription curve for $K^+\to\pi^+\nu\bar\nu$ to be used as described in Sec. III B to calculate limits corresponding to our data for any assumed π^+ spectrum. This curve is based on geometric efficiency curves I, II, and V of Fig. 2(a) with appropriate weighting factors. The arrow indicates the kinematic upper limit $T_{\pi^+}=127$ MeV.

The above discussion should be qualified by noting that the evidence for strong suppression of neutral leptonic currents is restricted to strangeness-changing processes, and, in particular, to K decays.

If a neutral current reaction involving a charged lepton pair, such as $K_L^0\to\mu^+\mu^-$, were observed to occur with a small branching ratio (there are now conflicting reports[8,9]), it could be interpreted as resulting either from a second-order weak interaction (essentially divergent) or from a combination of electromagnetic and first-order weak interactions.[20] Thus, the only kaon decays in which a second-order weak interaction might unambiguously be observed are $K^{\pm}\rightarrow\pi^{\pm}\nu\bar{\nu}$ and $K^0\rightarrow\pi^0\nu\bar{\nu}$.

Singh and Wolfenstein[21] have discussed possible effects of lepton nonlocality in the decays $K\rightarrow\pi e^+e^-$ and $K\rightarrow\pi\nu\bar{\nu}$. Our results place constraints on some of the models considered by them and by subsequent authors.

(i) Heavy-lepton models. There is continuing strong interest in the possible existence of a lepton, L, heavier than the muon. For $m_L < m_K$, one would expect such a lepton to be produced by $K^+\rightarrow L^+\nu$, and to decay predominantly by $L^+\rightarrow\pi^+\bar{\nu}$, yielding the net reaction $K^+\rightarrow\pi^+\nu\bar{\nu}$ (an extreme nonlocal process). Using the data of Klems, Hildebrand, and Stiening[1] and assuming canonical weak coupling for the L^+, Singh and Wolfenstein[21] have calculated the limit $m_L > (m_K - 0.03\text{ MeV})$ for the mass of the L. This limit is not significantly changed by our new data at lower pion energies.

A lepton, or "heavy muon," of lower mass, $m_L = 430$ MeV, has been suggested by Ramm[22] on the basis of structure—statistically not quite convincing—in the invariant mass of $(\mu\pi)$ and $(\mu\gamma)$ pairs produced in $K_{\mu 3}$ decay and in μ and ν scattering from nuclei. Vančura[23] has pointed out the difficulty of reconciling the weak production of such a lepton with the rather swift decay, $\tau_L < 10^{-12}$ sec, which would be necessary to explain the nonappearance of tracks of visible length which could be associated with such a particle in track-chamber experiments. From our data we find an upper limit (90% confidence) of 5.2×10^{-7} for the branching ratio of the two-step process $K^+\rightarrow L^+\nu\rightarrow\pi^+\nu\bar{\nu}$. Using this ratio and the analysis of Vančura[23] we obtain the limit

$$\Gamma(K^+\rightarrow L^+\nu)/\Gamma(K^+\rightarrow\mu^+\nu) < 9.5\times10^{-7}\ .$$

The magnitude of this ratio would seem to be strong evidence against the existence of a charged lepton at this mass.

We have extended this analysis to place limits on $K^+\rightarrow L^+\nu$ rates for all masses in the range $m_\pi < m_L < m_K$ as shown in Fig. 4. In calculating the upper limit to be inferred for $K^+\rightarrow L^+\nu$ from the limit on $K^+\rightarrow\pi^+\nu\bar{\nu}$, we have assumed the L^+ to be coupled to its own massless neutrino and have used the partial L-decay rates given by Tsai.[24]

(ii) Strong cubic model. The strong cubic intermediate vector-boson model developed by Okubo[25] (cutoff $\Lambda = 4$ GeV) and by Marshak, Yang, and Rao[26] ($m_W \approx 5$ GeV) predicts a branching ratio of 3×10^{-7} which corresponds to our 70%-confidence-level upper limit. We note that $K^+\rightarrow\pi^+\nu\bar{\nu}$ provides a more sensitive test of this model than $K^+\rightarrow\pi^+e^+e^-$ because of the existence of both μ and e neutrinos. Following Marshak's analysis[27] our limit implies a branching ratio for $K_S^0\rightarrow\mu^+\mu^-$ of $< 1.2\times10^{-7}$, which

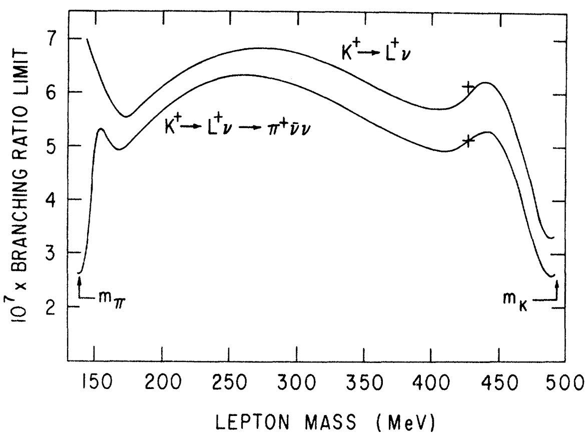

FIG. 4. Branching ratio upper limits (90% confidence) vs lepton mass for the heavy lepton model. The lower curve corresponds to the net process $K^+\rightarrow\pi^+\nu\bar{\nu}$ assuming $K^+\rightarrow L^+\nu$ followed by $L^+\rightarrow\pi^+\bar{\nu}$. The upper curve, $K^+\rightarrow L^+\nu$, is derived from the lower curve using Tsai's decay rates to obtain $\Gamma(L^+\rightarrow\pi^+\bar{\nu})/\Gamma(L^+\rightarrow\text{all})$ (Ref. 24). Crosses indicate limits for Ramm's heavy muon (Refs. 22 and 23). The shape of the curves is determined by the overlap of the pion energy spectrum with the prescription curve (Fig. 3). (Maximum overlap and hence lowest limit when pion spectrum is entirely within the upper peak of the prescription curve; i.e., when $m_L\approx m_K$ or $m_L\approx m_\pi$.)

is compatible with experiment,[11] and a ratio for $K_L^0\rightarrow\mu^+\mu^-$ in the range $(3.4-4.9)\times10^{-9}$, which is between the present experimental results.[9,10]

The intermediate-vector-boson model of Segrè[28] (cutoff $\Lambda\approx 300$ GeV) predicts a branching ratio for $K^+\rightarrow\pi^+\nu\bar{\nu}$ of $\approx 5\times10^{-6}$. Because of uncertainties in the pion spectrum for this model, the data of Klems *et al.*[1] near the kinematic limit did not provide an adequate test. With the additional data at lower pion energies the limits appear sufficiently low for a wide enough variety of spectra to exclude this theory (see Table II).

(iii) Renormalizable models. Recently much attention has been given to the class of models proposed by Weinberg[29] and shown by 't Hooft[30] to be renormalizable. Except in those versions in which neutral currents are forbidden, this theory has not yet been used to predict a branching ratio for $K^+\rightarrow\pi^+\nu\bar{\nu}$. Nor has it resulted in a prediction for the pion spectrum. Without such a spectrum we cannot give an exact experimental limit, but from the results given in Table II it appears likely that this limit must be less than 10^{-6}.

Note added in proof. A comparison of the K-decay data from our experiment and others (Tables I and II) with the new (presumably strangeness-conserving) neutrino-interaction data of the CERN [F. J. Hasert *et al.*, Phys. Lett. 46B 138 (1973)] and NAL [A. Benvenuti *et al.* (unpublished)] groups indicates that it may be important to draw a sharp distinction between strangeness-violating and strangeness-conserving hadronic neutral currents.

ACKNOWLEDGMENTS

We are grateful to Professor E. Segrè and Professor O. Chamberlain for their encouragement and support and to Dr. C. Wiegand, G. Lum, and H. Evans for valuable assistance during portions of the experiment. We thank the operating crew of the Lawrence Berkeley Laboratory Bevatron for their cooperation during the experimental run. One of us (G.D.C.) wishes to thank Professor T. Bowen for aid in preparing the dissertation on which this article is based.

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*Based on a dissertation submitted by G. D. Cable to the Department of Physics, The University of Arizona, in partial fulfillment of the requirements for the Ph.D. degree.

†Research supported by the U. S. Atomic Energy Commission and by the National Science Foundation under Grant No. 29717.

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