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RARE PION AND KAON DECAYS

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ABSTRACT

Some rare pion and kaon decays, which provide clues to the generation puzzle, are discussed. The $\pi\to e\nu/\pi\to\mu\nu$ branching ratio test of universality and the status of searches for $K^+\to\pi^+\nu\bar{\nu}$ are reviewed.

INTRODUCTION

The standard electroweak model[1] is a one generation theory in *which there is no rationale for multiple generations. Many* *ad hoc* extensions of this theory have been proposed which deal with the existence of extra generations, but none has been able to provide a satisfactory explanation for their properties or for their multiplicity. Rare kaon and pion decays play a significant role in probing the generation puzzle and in searching for new effects which would indicate directions beyond the standard model. A prime example is the prediction of the existence of the charm quark to explain the suppression of $K_L^\circ\to\mu\mu$ and other $\Delta S=1$ neutral current processes via the GIM mechanism.

In the quark sector, the Kobayashi-Maskawa[2] (K-M) scheme allows a possible *raison d'etre* for >3 generations which leads to the accommodation of a CP-violating phase in the quark-mixing matrix. CP-violation has only been observed in the neutral kaon system in $K_L^\circ\to2\pi$ decays and in the charge asymmetry in $K_{\ell3}^\circ$ decays. Limits on CP-violating effects in other kaon processes have been obtained by measuring the muon polarization normal to the decay plane in $K^+\to\pi^\circ\mu^+\nu_\mu$ and $K^\circ\to\pi^-\mu^+\nu_\mu$ decays. $K^+\to\pi^\circ\mu^+\nu_\mu$ is well suited to interpretation since there is no electromagnetic final state interaction. In a recent measurement, Campbell et al.[3] found a null result, $P_n = (-1.85 \pm 3.60)\times10^{-3}$, for the normal component of muon polarization. These measurements and others, notably those of the neutron electric dipole moment and of the parameter $|\varepsilon'/\varepsilon|$ in $K^\circ\to2\pi$ decays, are approaching the level necessary to confront predictions of alternate models, such as those in which CP-violation arises through a Higgs-fermion interaction.[4]

In the lepton sector, assumptions about the universality of electroweak interactions for the generations and the absence of flavor- (or generational-) changing reactions are built into the standard model. These hypotheses are suggested by rather exacting experimental evidence, such as the agreement between experiments and theory of electron and muon anomolous magnetic moments. The hypothesis of the universality of the weak interaction is tested most stringently using the branching ratio $\pi\to e\nu/\pi\to\mu\nu$.

Searches for rare kaon and pion decays, $K_L^\circ\to\mu e$, $K^+\to\pi^+\mu^\pm e^\mp$ and $\pi^\circ\to\mu^\pm e^\mp$, contribute information on lepton flavor violation. Table I shows the mass bounds that can be obtained for various hypothetical particles which mediate lepton flavor-violating reactions. For some theories, including some horizontal gauge theories, rare K decays provide the most stringent constraints, reaching into the multi-TeV mass region. $K\to\mu e$ and $K\to\pi\mu e$ will be discussed in a subsequent paper at this conference.

Table I Mass bounds (in TeV) from different processes*

Process	Higgs scalars	Pseudoscalar leptoquarks[a] (A)	Pseudoscalar leptoquarks[b] (B)	Vector leptoquarks	Experimental limit
$\frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to \mathrm{all})}$	0.2	–	–	–	1.9×10^{-10}
$\frac{\Gamma(\mu\to ee\bar{e})}{\Gamma(\mu\to \mathrm{all})}$	0.4	–	–	–	1.9×10^{-9}
$\frac{\Gamma(\mu A\to eA)}{\Gamma(\mu A\to \nu A')}$	11	1.5	11	60	7×10^{-11}(for S)
$\frac{\Gamma(K_L\to\mu\bar{e})}{\Gamma(K_L\to \mathrm{all})}$	7	1.8	5	93	2×10^{-9}
$\frac{\Gamma(K_L\to\mu\bar{\mu})}{\Gamma(K_L\to \mathrm{all})}$	4.7	1.2	3.6	62	9×10^{-9}
$\frac{\Gamma(K_L\to e\bar{e})}{\Gamma(K_L\to \mathrm{all})}$	7	1.8	5	95	2×10^{-9}
$\frac{\Gamma(K^+\to\pi^+\mu\bar{e})}{\Gamma(K^+\to \mathrm{all})}$	0.7	0.1	0.3	3.5	7×10^{-9}
$\Delta m(K_L-K_S)$	150	–	–	–	3.5×10^{-15} GeV

[a] The average fermion mass was taken to be 1 GeV.

[b] The average fermion mass was taken to be of order $\sqrt{m_\tau m_t}$ = 7.8 GeV for uμ couplings and $\sqrt{m_\tau m_b}$ = 3.1 GeV for dμ couplings.

* from O. Shanker, Nucl. Phys. B206, 253 (1982).

Studies of kaon and pion decays may also provide information on the numbers of light neutrinos and on neutrino masses. Experiments searching for the decay $K^+\to\pi^+x$ where x corresponds to $\nu\bar{\nu}$ pairs could confirm the predictions of the standard model with three generations (assuming the relevent heavy quark couplings were known) or they could indicate the presence of additional generations. These possibilities will be discussed in more detail below. The best upper limits on the muon neutrino mass have come from pion and kaon decay experiments.[5] Moreover, recent searches for medium mass neutrino admixtures in $K_{\ell 2}$ (Ref. 6) and $\pi_{\ell 2}$ decays have set stringent limits on possible couplings.

I will be discussing a few specific rare pion and kaon decay modes which have particular relevance to the lepton generation problem, while several other topics concerning rare pion and kaon decays will be dealt with by other speakers at this meeting.

$\pi^+\to e\nu_e$ DECAYS

In an important theorem on radiative corrections to $\pi_{\ell 2}$ decays, Marciano and Sirlin[7] proved that the $\pi\to e\nu/\pi\mu\nu$ branching ratio, calculated in the framework of the standard model and assuming electron-muon universality, is independent of strong interaction effects at the level of $\lesssim 0.5\%$. In essence, they found that the value

$$R = \frac{\Gamma(\pi\to e\nu + \pi\to e\nu\gamma)}{\Gamma(\pi\to\mu\nu + \pi\to\mu\nu\gamma)} = 1.233 \times 10^{-4} , \qquad (1)$$

determined in early calculations,[8] was a consequence of gauge invariance. This was confirmed in specific gauge model calculations by Goldman and Wilson.[9] The remaining theoretical uncertainties are related to pion structure dependent effects. Thus, the measurement of R provides a stringent test of universality in the context of the standard theory.

Significant deviations of the branching ratio from Eq. (1) would indicate the presence of new effects. For instance, the effect of pseudoscalar interactions induced by unusual Higgs couplings would be proportional to $1/m_H^2$, due to interference with the dominant axial vector term.[10] This can be contrasted with hypothetical lepton flavor-changing processes in which the reaction rates depend on $1/m_H^4$. The existence of pseudoscalar or vector leptoquarks could potentially affect the value of R.

Mixings of heavy neutrinos could change R from the standard model prediction as well. Neutrino mass eigenstates ν_i may be distinct from weak eigenstates $\nu_a (a = e, \mu, \tau, \ldots)$ and may be related through the nearly diagonal unitary transformation

$$\nu_a = \Sigma\, U_{ai} \nu_i . \qquad (2)$$

Shrock[11] has discussed the effects of such mixings on the decay of pseudoscalar mesons. The existence of massive neutrino states could lead to extra peaks in the lepton spectra in $\pi_{\ell 2}$ or $K_{\ell 2}$ decays. For $\pi\to e\nu$ the decay rate is helicity suppressed by a factor 10^4 for massless neutrinos. For massive neutrinos this suppression is not effective, making $\pi\to e\nu$ (or $K\to e\nu$) a favored reaction with which to search for massive neutrinos coupled to electrons.

An early measurement by Anderson et al.[12] found $R = (1.21 \pm 0.07)\times 10^{-4}$ in agreement with Eq. (1). Subsequently, an experiment by Di Capua et al.[13] obtained[14] $R = (1.274 \pm 0.024)\times 10^{-4}$, which differs from the theoretical prediction by $(3.3 \pm 1.9)\%$. A recent measurement of the branching ratio[15] done at TRIUMF will be discussed below.

The experimental set-up for the TRIUMF experiment is shown in Fig. 1. Stopped pions decayed directly via $\pi^+\to e^+\nu_e$ or through the π-μ-e chain to positrons, which were detected in a 46 cm × 51 cm NaI(Tℓ) crystal preceded by plastic scintillators. The intrinsic resolution of the crystal was $\Delta E/E \sim 3.5\%$ (FWHM) at 70 MeV. Since NaI detectors are sensitive to both charged particles and gamma rays, the measurement included inner bremsstrahlung photons emitted in the direction of the positrons. Figure 2a shows the positron spectrum for both $\pi^+\to e^+\nu_e$ and $\mu^+\to e^+\nu_e\bar{\nu}_\mu$ events taken from 2 to 22 nsec after the pion stop and Fig. 2b shows the pure $\pi^+\to e^+\nu_e$ spectrum after background subtraction.

Use of the energy distribution and timing distribution of the π-μ-e chain for normalization contributed to the minimization of systematic errors in the determination of the branching ratio. The

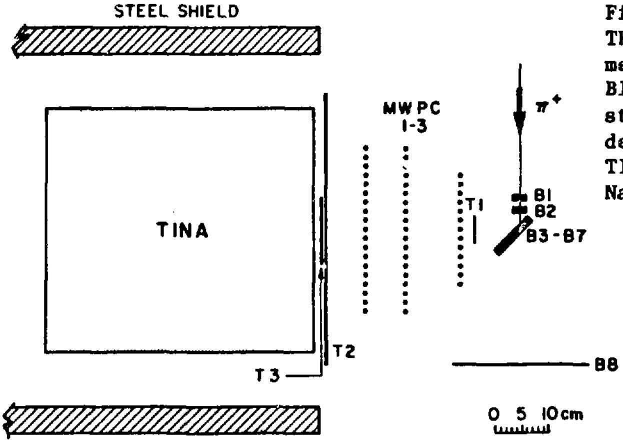
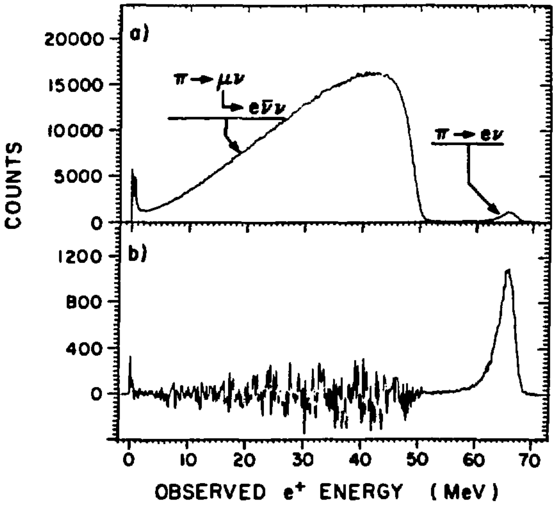


Fig. 1. Setup for the TRIUMF $\pi\to e\nu$ experiment. Scintillators B1-B8 detect pion stops, T1-T3 detect decay positrons and TINA is a large NaI(Tℓ) crystal.

Fig. 2. Positron spectrum following pion decay. (a) The full spectrum 2 to 22 ns after the pion stop. (b) The spectrum of $\pi\to e\nu$ decays obtained after subtraction of the normalized μ-decay distribution.



branching ratio was obtained using the expression[13]

$$R = \frac{\lambda_\mu}{\lambda_\pi-\lambda_\mu}\;\frac{N_{\pi e}\left(1-e^{-(\lambda_\pi-\lambda_\mu)t_s}\right)}{N(2)_{\pi\mu e}e^{\lambda_\mu t_s}-N(1)_{\pi\mu e}}\,, \tag{3}$$

where λ_μ and λ_π are the muon and pion decay constants, $N(1)_{\pi\mu e}$ and $N_{\pi e}$ are the numbers of π-μ-e and π-e events detected during an early interval, and $N(2)_{\pi\mu e}$ is the number of π-μ-e events recorded during an identical interval 173.5 nsec or 6.7 pion lifetimes later. This method of determining R is independent of several important sources of possible uncertainties, including the displacement of the first interval from the arrival time of the pion, the positron detector solid angle, the absolute width of the two time bins (as long as they are identical) and the fraction of muons in the beam or the contribution from decays of muons left in the target by previous pions stops. A second method, which relied on fitting the timing distributions of π-e and π-μ-e events, was also used.

The branching ratio obtained was

$$R = \Gamma(\pi\to e\nu + \pi\to e\nu\gamma)/\Gamma(\pi\to\mu\nu+\pi\to\mu\nu\gamma)$$
$$= 1.218 \pm 0.014 \times 10^{-4} \ . \qquad (4)$$

The statistical and estimated systematic uncertainties are comparable with the latter principally due to uncertainty in the NaI response function.

This result is in agreement with the prediction Eq. (1), based on the hypothesis of electron-muon universality within the context of the standard model. A quantitative test of universality can be obtained by comparing the experimental result Eq. (4) with the theoretical prediction $R_{th} = (1.233 \times 10^{-4}) \cdot (f_\pi^e/f_\pi^\mu)^2$, assuming distinct effective coupling constants f_π^e and f_π^μ for the electron and muon modes. Then

$$\frac{f_\pi^e}{f_\pi^\mu} = 0.9939 \pm 0.0057 \ . \qquad (5)$$

A limit on the contribution of a pseudoscalar coupling to $\pi_{\ell 2}$ decay can also be deduced:

$$f_p = (-0.0061 \pm 0.0057) f_\pi m_e \ . \qquad (6)$$

Limits on masses of hypothetical particles contributing to pseudoscalar interactions in $\pi_{\ell 2}$ decay have been obtained by Shanker.[10] For example, Eq. (6) implies a mass limit $m_H > 350$ GeV for charged Higgs particles contributing to $\pi_{\ell 2}$ decay in models where Higgs-fermion couplings are proportional to heavy fermion masses.

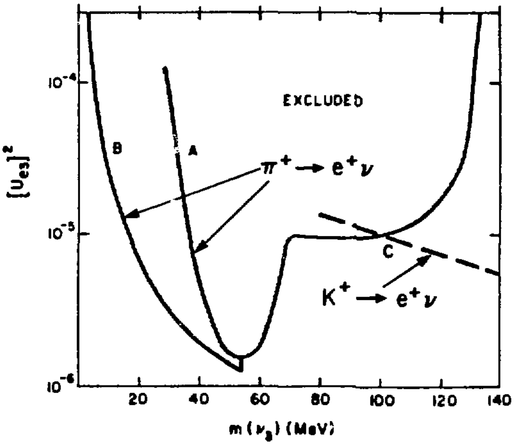
The search for heavy neutrino admixtures in the $\pi\to e\nu$ spectrum[16] was carried out using the data in Fig. 2. The low energy peaks were due to the zero energy pedestal and 511 keV annihilation radiation. No evidence for heavy neutrino states has been found. The results in Fig. 3. indicate the 90% C.L. upper limits in the mixing parameter $|U_{e3}|^2$ for heavy neutrinos coupled to electrons in a 3 neutrino world.

Current results on searches for heavy neutrinos coupled to muons in $K\to\mu\nu$ and $\pi\to\mu\nu$ decays will be reported elsewhere at this conference. New experiments to measure more accurately the $\pi\to e\nu$ branching ratio and to improve the searches for heavy neutrino admixtures have been proposed at both SIN and TRIUMF.

π° DECAYS

Two rare π° decays will be discussed: $\pi^\circ\to\nu\bar\nu$ and $\pi^\circ\to\mu e$. Neither mode has been the subject of a dedicated experiment, although limits have been derived from existing data. Rare π° decays such as these may best be studied using a tagged π° source derived from $K_{\pi 2}$ decay $K^+\to\pi^+\pi^\circ$, which has a branching ratio of 21%. The energy and direction of the π° can be determined by detection of the π^+, which has energy of 108 MeV in the kaon rest system.

Fig. 3. The 90% C.L. limit on the mixing parameter $|U_{e3}|^2$. Curve A was obtained from the search for monoenergetic peaks; curve B was obtained from the $\pi \to e\nu$ branching ratio measurement; curve C was obtained from $K \to e\nu$ data (see Ref. 11).



a) $\pi^\circ \to \nu\bar{\nu}$

The decay $\pi^\circ \to \nu\bar{\nu}$ is forbidden for massless Weyl neutrinos in the standard model. It is an allowed process independent of lepton flavor-mixing parameters for massive neutrinos with the standard neutral current couplings. The branching ratio

$$B = \frac{\Gamma(\pi^\circ \to \nu\bar{\nu})}{\Gamma(\pi^\circ \to \mathrm{all})} = 3.2 \times 10^{-8}\left(\frac{m_\nu}{m_\pi}\right)^2\left[1-\left(\frac{2m_\nu}{m_\pi}\right)^2\right]^{1/2} . \qquad (7)$$

For $m_\nu = 50$ MeV, $B \cong 10^{-9}$ compared to the existing limit[17] $B < 2.4 \times 10^{-5}$ (90% C.L.) obtained by Herczeg and Hoffman. Gaillard et al.[18] also have considered the π° decay to photinos, the supersymmetric partners of the photon, and find under some conditions $\pi^\circ \to \tilde{\gamma}\tilde{\gamma}$ could be appreciable. New experiments searching for $K^+ \to \pi^+ x$ could considerably improve the present limit as well.

b) $\pi^\circ \to \mu e$

A branching ratio limit for $\pi^\circ \to \mu e$ has been obtained[19] by examining data from a search for $K^+ \to \pi^+ \mu e$. The (90% C.L.) result was

$$B(\pi^\circ \to \mu e) = \frac{\Gamma(\pi^\circ \to \mu e)}{\Gamma(\pi^\circ \to \mathrm{all})} < 1.4 \times 10^{-8} . \qquad (8)$$

Assuming a general parity conserving interaction,

$$B(\pi^\circ \to \mu e) = 10^5(|M|^2) ,$$

where M represents the axial-vector (A) and psuedoscalar (P) contributions as

$$\begin{aligned} M &= G\, m_\mu m_\pi\, f^A + 8\sqrt{2}\, G\, m_\pi^2\, f^P \\ &= 1.6 \times 10^{-7} f^A + 2.3 \times 10^{-6} f^P , \end{aligned} \qquad (9)$$

and f^A and f^P are the coupling strengths relative to $G/\sqrt{2} \sim 10^{-5}/m_p^2$, respectively. Using the limit Eq. (8) above, it is found that

$$f^A < 5.3 \text{ for } f^P = 0 \;,$$
$$f^P < 0.4 \text{ for } f^A = 0 \;. \tag{10}$$

$\pi^\circ \to \mu e$ decay can occur in models containing lepton flavor-changing axial-vector or pseudoscalar interactions of Higgs particles, leptoquarks or exotic gauge bosons. As an example consider Higgs exchange for which the pseudoscalar coupling could be expected to have the form

$$f_P \sim \frac{m_t m_\tau}{m_H^2} \;, \tag{11}$$

where m_t and m_τ are heavy fermion masses and m_H is the mass of the Higgs particle. Using $m_t = 30$ GeV, $m_\tau = 1.8$ GeV and Eq. (10) it is found that $m_H > 12$ GeV. Although other flavor-changing processes, such as muon electron conversion, are apparently more sensitive than $\pi^\circ \to \mu e$ to such exotic interactions it would be worthwhile to improve the experimental limits on this process.

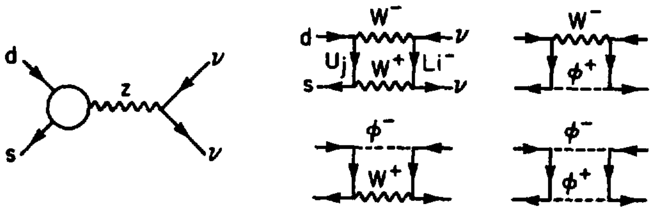
$K \to \pi^+ x$ DECAYS

The decay $K^+ \to \pi^+ x$, where x is any combination of extremely weakly interacting or unobservable particles, is particularly interesting from several points of view. In principle, when $x = \nu\bar{\nu}$, the decay rate

$$\Gamma(K^+ \to \pi^+ x) = \sum_{i=1}^{N_\nu} \Gamma(K^+ \to \pi^+ \nu_i \bar{\nu}_i) \tag{12}$$

could provide a test of the minimal model with three generations ($N_\nu = 3$) or it could indicate the presence of additional generations. The dominant second order weak diagrams affecting $K \to \pi\nu\bar{\nu}$ are shown in Fig. 4.[20] The two classes of diagrams include Z exchange graphs generated by $d\bar{s}Z$ coupling and box graphs which depend on exchange of a massive lepton (L_i). In the standard theory the amplitudes will involve factors

$$U^*_{jd}\, U_{js} \left(\frac{m_{q_j}}{m_W}\right)^2 \ln\left(\frac{m_W^2}{m_{q_j}^2}\right), \tag{13}$$



(a) (b)

Fig. 4. (a) The Z exchange diagram contributing to $d\bar{s} \to \nu\bar{\nu}$. (b) The box diagrams for $d\bar{s} \to \nu\bar{\nu}$ including exchange of unphysical charged Higgs. From Ref. 20.

where q_j are the charge 2/3 quarks ($j = u,c,t$), m_W is the W boson mass and $m_t^2 \ll m_W^2$ is assumed.[21] U_{ij} are the elements of the K-M mixing matrix. The t quark contribution is expected to dominate unless the t-s or t-d mixing angles are extremely small. An upper limit for the rate $K \to \pi\nu\bar{\nu}$ shown in Fig. 5 has been derived[22] as a function of t quark mass from constraints provided by the observed rate for $K \to \mu\mu$. For $m_t \approx 20$ GeV, $B\left(\Gamma(K^+ \to \pi\bar{\nu}\nu)/\Gamma(K+ \to \text{all})\right) \lesssim 5\times10^{-9}$.[23] Lower bounds based on the K_L-K_S mass difference also have been obtained,[22] but suffer from many uncertainties. New measurements of the B lifetime and decay and of other processes should enable better constraints to be derived on the relevant K-M mixing parameters needed to calculate the rate for $K \to \pi\nu\bar{\nu}$.[24] Thus, within the standard model this process could provide constraints on the t quark mass and mixing parameters. If m_t and the mixing parameters are already known, observation of this decay would provide a direct test of weak radiative corrections in the framework of the standard model.[23] If the observed branching ratio or limit were of the order of the limits in Fig. 5, then an upper bound on the number of light neutrino generations could be inferred.[22]

Observation of a branching ratio B well above the limits in Fig. 5 would almost certainly signal new physics. In addition to the existence of extra neutrino generations, other more exotic possibilities for x have been suggested. These include the axion and the (Majorana) supersymmetric partners of the photon and the Higgs particle. Shrock[21] has estimated that if tree level graphs dominate the decay $K^+ \to \pi^+\tilde{\gamma}\tilde{\gamma}$, where the photino $\tilde{\gamma}$ is the supersymmetric partner of the photon, then the branching ratio could be as large as 10^{-7}. Ellis and Hagelin[22] also find that the decay into Shigges $K^+ \to \pi^+\tilde{H}\tilde{H}$ could compete with $K \to \pi\nu\bar{\nu}$.

Wilczek[26] has proposed that an axion-like particle, the familon, arises in a theory with spontaneously broken flavor symmetry. This approach offers the hope of understanding the distribution of fermion masses. The interactions of familons will lead to flavor-changing neutral current decays, such as $K^+ \to \pi^+ f$ with a branching ratio

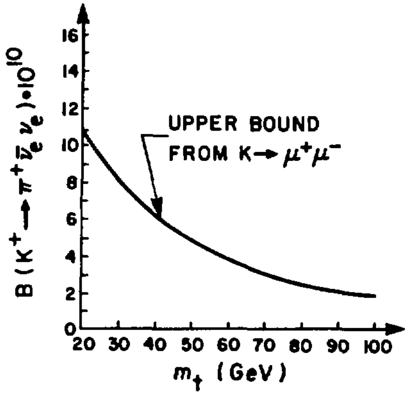


Fig. 5. Upper bounds on $B(K^+ \to \pi^+\nu\bar{\nu})$ derived from $K \to \mu^+\mu^-$. From Ref. 22.

$$B_F = \frac{\Gamma(K^+\to\pi^+ f)}{\Gamma(K^+\to\pi^+\pi^\circ)} = \frac{1.3\times10^{14}\ \mathrm{GeV}}{F_{K\pi}^2}\ , \qquad (14)$$

where $F_{K\pi}$ is of the same order as the symmetry breakdown scale. Since $F_{K\pi}$ should be in the range 10^9-10^{12} (from cosmological considerations), $K^+\to\pi^+ f$ could be observable. The present limit discussed below yields $F_{K\pi} \gtrsim 5\times10^{10}$ GeV.

Previous searches for $K^+\to\pi^+\nu\bar{\nu}$ have been reported by Asano et al.[25] (KEK), who found $\Gamma(K\to\pi^+\nu\nu)/\Gamma(K^+\to\mathrm{all}) < 1.4\times10^{-7}$ (90% C.L.), and by Cable et al.[27] (LBL), who found $B(K\to\pi\nu\bar{\nu}) < 5\times10^{-7}$. The KEK experiment also gave limits on the branching ratio involving an axion-type particle $B(K^+\to\pi^+ a) < 3.8\times10^{-8}$ and on $B(K^+\to\pi^+\gamma\gamma) < 8.4 \times10^{-6}$. Both experiments were done using stopped kaons and both detected the pions in a simple range telescope. Highly sensitive recognition of events with single pions and efficient photon vetoing were sought in these efforts.

Range spectra of pions and muons in scintillator for $K^+\to\pi^+\nu\bar{\nu}$ and other kaon decays are shown schematically in Fig. 6, assuming finite resolution. In order to eliminate many potential sources of background, only the region of $K^+\to\pi^+\nu\bar{\nu}$ phase space above the $K^+\pi^+\pi^\circ$ peak (19% of the total) was examined in the KEK experiment. The two body decay $K^+\to\pi^+\pi^\circ$ (branching ratio 21.2%) would be indistinguishible from $K^+\to\pi^+\nu\bar{\nu}$ if both the photons from π° decay are missed. Other important backgrounds could arise due to combinations of accidental coincidences and detector inefficiencies. Potential background sources come from misidentification of a muon from $K^+\to\mu^+\nu\gamma$ decay, from inelastic scattering of beam pions, and from $K^+n\to K^\circ p$ reactions in the target followed by $K_L^\circ\to\pi^+\mu^-\nu$ decay.

The setup for the KEK experiment is shown in Fig. 7. 530 MeV kaons were identified by a time-of-flight Cerenkov counter system and were stopped in a scintillator target at a rate of 0.8×10^4/sec. Pions in the energy range above the $K^+\to\pi^+\pi^\circ$ peak $116 < T_\pi <$ 127 MeV were degraded and then stopped in a scintillation counter range stack covering a solid angle of 8%. Stopping particles passed through an iron degrader and water Cerenkov counter used to reject some muon events. Pions were identified by observation of the π-μ-e decay chain. Each range counter with dimensions 1 m × 30 cm × 1 cm was viewed from one end by a 2" phototube whose signal was processed in a multiplexed system of 500 MHz transient digitizers. Observation of the 4 MeV π-μ decay within 2.5 to 50 nsec, the principal step in distinguishing a pion from a muon, was required to be isolated in the pion stopping counter. Figure 8 shows the energy spectrum of π-μ decays. Only 5% of the isolated accidentals passed an energy cut applied to reject muon events. Subsequent μ-e decays also were required to originate in the pion stopping counter. On the opposite side of the target was a 12 radiation length array of Pb-glass Cerenkov counters covering approximately 2π sr. The measured inefficiency for detection of $\pi^\circ\to\gamma\gamma$ decays from $K^+\to\pi^\circ\pi^+$ was 3.5×10^{-4}. The detection efficiency for photons below 30 MeV (such as those arising from $K^+\to\mu\nu\gamma$) was negligible. The overall acceptance of the KEK experiment for $K^+\to\pi\nu\bar{\nu}$ was 1.2×10^{-3}, including geometrical acceptance, kinematic cuts and other factors listed in Table II.

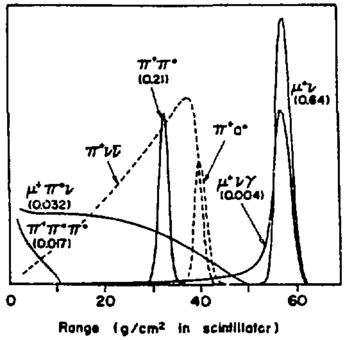


Fig. 6. The range spectra in scintillator for $K^+\to\pi^+\nu\bar{\nu}$ and potential background processes due to other decays. Finite resolution is assumed. Numbers in parentheses are branching ratios. From Ref.[25].

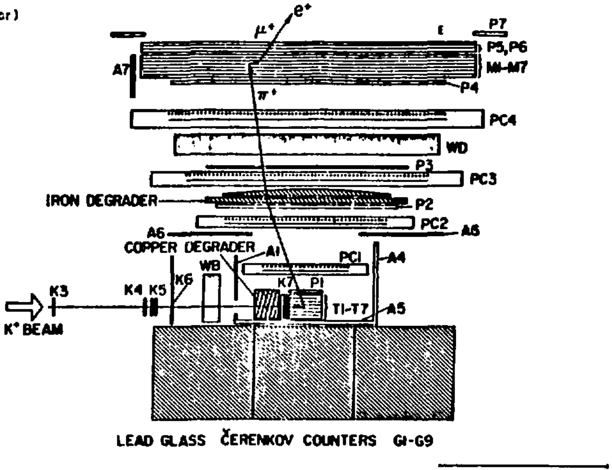


Fig. 7. The setup for the KEK search for $K^+\to\pi^+\nu\bar{\nu}$.

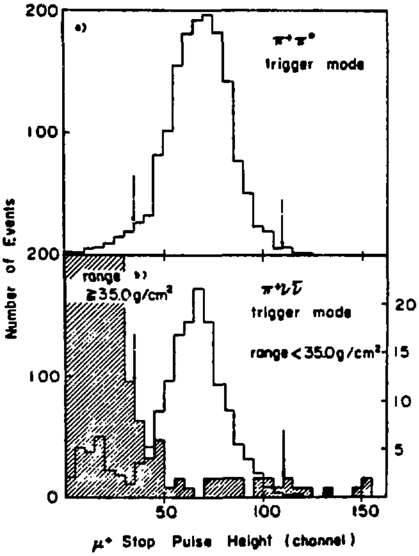


Fig. 8. The pulse height spectrum for 4 MeV muons from $\pi^+\to\mu^+\nu_\mu$ decay in the KEK experiment[25] in the $K^+\to\pi^+\pi^0$ trigger mode (a) and in the $K^+\to\pi^+\nu\bar{\nu}$ trigger mode (b). The shaded events are those with ranges larger than 3.5.0 gm/cm^2 (above the $\pi^+\pi^0$ peak) and their scale is shown on the right.

Table II Acceptance factors for the KEK $K \to \pi \nu \bar{\nu}$ experiment*

Spectrum cut	0.19
Solid angle	0.07
Timing cuts	
K-π decay	0.78
π-μ decay	0.63
Pion absorption	0.49
π-μ decay in stop counter	0.88
Reconstruction efficiency	0.8
μ-e efficiency	0.67
μ-e timing cut	0.88
4 MeV π-μ pulse cut	0.97
Other	0.95
Overall efficiency	0.0012

*Ref. 25

The earlier LBL experiment used a similar technique and, in a second phase for which the setup is shown in Fig. 9, an attempt was made to observe pions of energy below the 2 body $K^+ \to \pi^+ \pi^0$ peak. In this case, the Pb-glass photon veto covered nearly 4π sr, giving a measured π^0 detection inefficiency upper limit $<2 \times 10^{-5}$. In

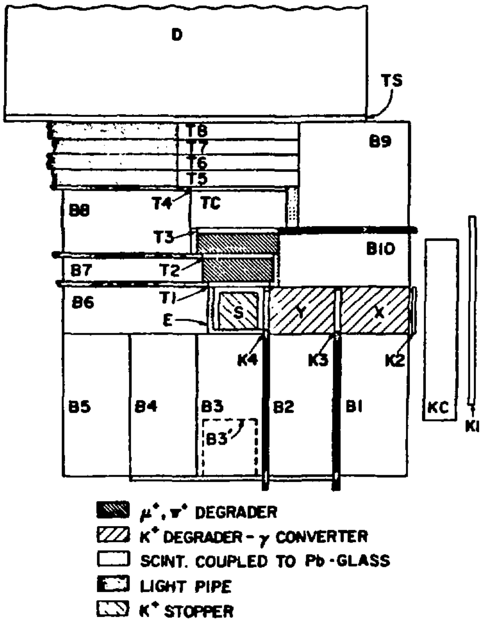


Fig. 9. The setup for the LBL search for $K^+ \to \pi^+ \nu\nu$.

addition, a rough measurement of the photon veto inefficiency for the energy range $30 < E < 50$ MeV gave 1.3%.

Certainly further searches for $K \rightarrow \pi x$ would be desirable. It also appears feasible to reach experimental sensitivities $O(10^{-10})$, which would confront the predictions of the standard model. This might be done by having $\gtrsim 2\pi$ sr acceptance for pions, by using highly sensitive pion identification techniques involving momentum, kinetic energy and range measurements, as well as π-μ-e chain observation, and by developing a fast photon veto which would allow π° detection inefficiency to be $\lesssim 10^{-6}$. Recently a proposal to reach this level has been submitted to BNL by a BNL-Columbia-Princeton-TRIUMF group.

CONCLUSION

Rare pion and kaon decay experiments continue to be a rich field for studying the generation puzzle and conventional weak interactions and for searching for new effects. A prime example is the decay $K^+ \rightarrow \pi^+ x$, where x represents any extremely weakly interacting particles, such as neutrino antineutrino pairs, supersymmetric particles, such as photinos, or axions. A window of up to three orders of magnitude exists between the current experimental limit and the standard model predictions for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ in which to search for evidence of new physics.

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