tron-muon universality, is independent of strong interaction effects at the level of \( \lesssim 0.5\% \). In essence, they found that the value

\[
R = \frac{\Gamma(\tau^+\mu^-\nu_\mu)}{\Gamma(\tau^+e^-\nu_e)} = 1.233 \times 10^{-4},
\]

(1)
determined in early calculations,\(^8\) was a consequence of gauge invariance. This was confirmed in specific gauge model calculations by Goldman and Wilson.\(^3\) 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.\(^9\) This can be contrasted with hypothetical lepton flavor-changing processes in which the reaction rates depend on \( 1/m_h^n \). 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 \( \nu_i \) may be distinct from weak eigenstates \( \nu_e, \nu_\mu, \nu_\tau \) and may be related through the nearly diagonal unitary transformation

\[
\nu_e = \sum_i U_{ei} \nu_i
\]

(2)

Shrock\(^1\) 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 \( K_L \) or \( K_S \) decays. For \( \tau^+e^- \) the decay rate is helicity suppressed by a factor \( 10^8 \) for massless neutrinos. For massive neutrinos this suppression is not effective, making \( \tau^+e^- \) or \( \tau^+\mu^- \) 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 \( R = (1.274 \pm 0.024) \times 10^{-4} \), 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 \( \pi^-e^-\nu_e \) or through the \( \pi^-e^- \) chain to positrons, which were detected in a 46 cm x 51 cm NaI(Tl) crystal preceded by plastic scintillators. The intrinsic resolution of the crystal was \( \Delta E/E \approx 3.5\% \) (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 \( \pi^-e^-\nu_e \) and \( \pi^-\mu^-\nu_\mu \) events taken from 2 to 22 nsec after the pion stop and Fig. 2b shows the pure \( \pi^-e^-\nu_e \) spectrum after background subtraction.

Use of the energy distribution and timing distribution of the \( \pi^-e^- \) chain for normalization contributed to the minimization of systematic errors in the determination of the branching ratio. The

\[
R = \frac{\lambda_\mu}{\lambda_\tau} \frac{N_{\pi e}}{N_{\pi e} - N_{\pi e}}
\]

(3)

where \( \lambda_\mu \) and \( \lambda_\tau \) are the muon and pion decay constants, \( N(1)_{\pi e} \) and \( N_{\pi e} \) are the numbers of \( \pi^-e^- \) and \( \pi^-e^- \) events detected during an early interval, and \( N(2)_{\pi e} \) is the number of \( \pi^-e^- \) events recorded during an identical interval 173.5 nsec or 6.7 pion lifetimes later. This method of determining \( R \) is independent of some possible sources of uncertainty, 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 contribu-
\[ f_A^p < 5.3 \text{ for } f_A^p = 0 , \]
\[ f_P^p < 0.4 \text{ for } f_A^p = 0 . \]  

(10)

The decay of \( K^+ \rightarrow \mu^+ \nu_\mu \) 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

\[ f_p \sim \frac{m_L m_{\mu}}{m_H^2} , \]  

(11)

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

**K^+ \rightarrow \tau^+ \nu_x** DECAYS

The decay \( K^+ \rightarrow \tau^+ \nu_x \), where x is any combination of extremely weakly interacting or unobservable particles, is particularly interesting from several points of view. In principle, when \( x = \nu_x \), the decay rate

\[ \Gamma(K^+ \rightarrow \tau^+ \nu_x) \leq \frac{N}{f_{\pi}} \Gamma(K^0 \rightarrow \mu^+ \nu_\mu) \]  

(12)

could provide a test of the minimal model with three generations \((N = 3)\) or it could indicate the presence of additional generations. The dominant second order weak diagrams affecting \( K^+ \rightarrow \nu_x \nu_x \) are shown in Fig. 4.  

The two classes of diagrams include Z exchange graphs generated by \( d \bar{Z} \) coupling and box graphs which depend on exchange of a massive lepton \( \left( L_1 \right) \). In the standard theory the amplitudes will involve factors

\[ U_{jd} U_{js} \left( \frac{m_{L_1}}{m_H} \right)^2 \ln \left( \frac{m_{L_1}^2}{m_{L_3}^2} \right) , \]  

(13)

**Fig. 4. (a) The Z exchange diagram contributing to ds+\nu. (b) The box diagrams for ds+\nu including exchange of unphysical charged Higgs. From Ref. 20.**

where \( q_1 \) are the charge 2/3 quarks \((u, c, t)\), \( m_W \) is the W boson mass and \( m_Z^2 < m_W^2 \) is assumed.  

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 \( K^+ \rightarrow \nu_x \nu_x \) shown in Fig. 5 has been derived as a function of t quark mass from constraints provided by the observed rate for \( K^+ \nu_x \nu_x \). For \( m_t = 20 \text{ GeV} \), \( B(K^+ \rightarrow \nu_x \nu_x) / B(K^+ \rightarrow \mu_x \nu_x) \leq 5 \times 10^{-3} \).  

Lower bounds based on the K_{L2}-K_{S2} mass difference also have been obtained, but suffer from many uncertainties. New measurements of the B lifetime and decay of and other processes should enable better constraints to be derived on the relevant K-M mixing parameters needed to calculate the rate for \( K^+ \nu_x \nu_x \). Thus, within the standard model this process could provide constraints on the t quark mass and mixing parameters. If \( q_1 \) 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. 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.

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 has estimated that if tree level graphs dominate the decay \( K^+ \rightarrow \nu_x \nu_x \), where the photon \( \gamma \) is the supersymmetric partner of the photon, then the branching ratio could be as large as \( 10^{-7} \). Ellis and Hugelin also find that the decay into Higgs \( K^+ \rightarrow \nu_x \nu_x \) could compete with \( K^+ \nu_x \nu_x \).

Wilkosz has proposed that an axion-like particle, the familion, arises in a theory with spontaneously broken flavor symmetry. This approach offers the hope of understanding the distribution of fermion masses. The interactions of familions will lead to flavor-changing neutral current decays, such as \( K^+ \rightarrow \tau^+ \nu \) with a branching ratio

**Fig. 5. Upper bound on B(K^+ \rightarrow \nu_x \nu_x) derived from K^+ \nu_x \mu_x. From Ref. 22.**
Table II Acceptance factors for the KEK K\(\rightarrow\pi\nu\nu\) experiment

<table>
<thead>
<tr>
<th>Component</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum cur</td>
<td>0.19</td>
</tr>
<tr>
<td>Solid angle</td>
<td>0.07</td>
</tr>
<tr>
<td>Timing cuts</td>
<td>0.78</td>
</tr>
<tr>
<td>K–(\pi) decay</td>
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</tr>
<tr>
<td>(\pi\mu) decay</td>
<td>0.49</td>
</tr>
<tr>
<td>Pion absorption</td>
<td>0.88</td>
</tr>
<tr>
<td>(\pi\mu) decay in stop counter</td>
<td>0.8</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.67</td>
</tr>
<tr>
<td>4 MeV (\pi\mu) pulse cut</td>
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</tr>
<tr>
<td>Other</td>
<td>0.95</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

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\(\rightarrow\pi\pi\) peak. In this case, the Pb-glass photon veto covered nearly 4\(\pi\) sr, giving a measured \(\pi\) detection inefficiency upper limit \(2 \times 10^{-5}\). In 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 \(\geq 2\pi\) or acceptance for pions, by using highly sensitive pion identification techniques involving momentum, kinetic energy and range measurements, as well as \(\pi\mu\) \(e\) chain observation, and by developing a fast photon veto which would allow \(\pi\) detection inefficiency to be \(\leq 1\times 10^{-5}\). 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 winow of up to three orders of magnitude exists between the current experimental limit and the standard model predictions for K\(\rightarrow\pi\pi\nu\nu\) in which to search for evidence of new physics.

REFERENCES

5. See H. Daum et al., Phys. Lett. 76B, 126 (1978) and this conference.
6. See R. Hayano, this conference. See also J. Deutch et al. (to be published) for additional limits on heavy neutrinos coupled to muons.