DHL--35086

BNL-35086

DE84 016435

DE 84 - 016435 - 5

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Status of Rare Decay Experiments

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STATUS OF RARE DECAY EXPERIMENTS

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I will discuss a number of current and future rare μ and K decay experiments. We call these decays 'rare' because we know they are not common, however, most of them have never been observed at all. Therefore they are not rare in the sense the white rhinoceros is, they are rare in the sense that the pink rhinoceros is rare.

By and large the muon experiments are running now, while the kaon experiments are still at the proposal stage. I'll give what results there are for the muon experiments while my discussion of the kaon work is necessarily of the 'coming attractions' variety.

The physics in both cases is mainly beyond the standard model ($SU(3) \times SU(2) \times U(1)$ with 3 generations). After the triumphs of this model it may seem ungrateful to look for its warts, but it is clear that it leaves many questions unanswered. Among others--why are there multiple generations and how many are there? What is the relationship between leptons and quarks? Why are the masses what they are? What is the origin of CP violation? Etc.

In order to answer these questions we have to look beyond the boundaries of the model. One of the most incisive ways to do this is to search for processes which are forbidden or at least highly

suppressed in the model. The observation of such a process would clearly signal the presence of new physics, and make possible the elucidation of its properties.

One class of forbidden processes are those which violate lepton flavor conservation. Examples are $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu^- A \rightarrow e^- A$, $K_L^0 \rightarrow e\mu$, $K^+ \rightarrow \pi\mu e$, $D^0 \rightarrow \mu e$, $\tau \rightarrow \mu\gamma$, etc. Examples of processes which are highly suppressed by the detailed structure of the standard model are $K_L^0 \rightarrow e^+e^-$ and $K^+ \rightarrow \pi^+\nu\bar{\nu}$. $K_L^0 \rightarrow e^+e^-$ is suppressed by some 3 or 4 orders of magnitude below $K_L^0 \rightarrow \mu^+\mu^-$ by helicity conservation (and $K_L^0 \rightarrow \mu^+\mu^-$ is already very suppressed by the GIM mechanism). The branching ratio for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is suppressed by the GIM mechanism to $\sim 10^{-10}$.

Lepton flavor violation occurs naturally in many types of models, a number of which have been discussed at this meeting. An incomplete list of these models are:

- 1) Almost standard mode with $m_\nu \neq 0$.
- 2) Almost standard model with extra generations containing heavy neutrinos.
- 3) Almost standard model with flavor changing Higgs.
- 4) GUTs with low mass B & L violating Higgs.
- 5) Extended technicolor.
- 6) Some supersymmetric models.
- 7) Models containing horizontal gauge symmetries.
- 8) Constituent models.

Figure 1 shows how some of these mechanisms mediate lepton flavor violation. Few or no regularities obtain in all models. Some mechanisms require both quarks and leptons to participate in the LFV, others are diagonal. In some models $\mu \rightarrow eee$ occurs as an electromagnetic correction to $\mu \rightarrow e\gamma$, in others the reverse is true. In most models $K_L^0 \rightarrow \mu e$ occurs with a higher rate than $K^+ \rightarrow \pi^+e\mu$ because of the phase space, but in models where the mediating interaction is vector, $K_L^0 \rightarrow \mu e$ does not occur at all. Therefore, one is well advised to look for all accessible processes.

Fig. 1. Flavor violating processes. a) $\mu + e \gamma$ via a heavy lepton, (b) $K^+ \rightarrow \pi e \mu$ via leptoquark exchange, c) $K_L^0 \rightarrow \mu e$ via constituent exchange, d) $\mu \rightarrow e e e$ via horizontal gauge boson exchange.

In general the new interaction responsible for LFV is mediated by some heavy object. Typically the rate for the process is $\propto g^2 g'^2 M_H^{-4}$ where M_H is the heavy particle mass and the g 's are its coupling constants at the fermion vertices. Table I¹ gives a comparison of the mass probed by different processes in various models for a fixed branching ratio sensitivity of 10^{-10} . The most striking information in the table is the mass scale in some of the models - tens or hundreds of TeV! This is higher than can be accessed even by the proposed SSC. Thus it is fair to say that these are really frontier experiments. The Table also illustrates the variations in relative sensitivity of the different processes as one goes from model to model (or even changes the parameters of a given model).

There have been relatively few rare kaon decay experiments in recent years. New data on lepton flavor violation has been virtually non-existent for at least ten years, and even before that it tended to be a by-product of other, more fashionable physics. Thus the new dedicated experiments anticipate large improvements (100-10000) on the previous branching ratio upper limits of $\approx 10^{-8}$.

By contrast the muon experimentors have been much more constant in their pursuit of lepton flavor violation, and they have pushed the limits down to the $\approx 10^{-10}$ level. The current round of experiments aim to improve these limits by 10-100 fold. I will report on three experiments which are in the process of taking data. They are quite ambitious undertakings aimed at reducing branching ratio upper limits currently around 10^{-9} - 10^{-10} down to sensitivities of 10^{-11} - 10^{-12} . Although not physically large by modern high energy physics standards ($\approx 1 \text{ m}^3$) these are no longer table top experiments. Technologically they are quite sophisticated, employing in one case a large array of sodium iodide crystals, in another a TPC, and in all three, state of the art electronics. Although many of the techniques are familiar to high

energy experimentalists there are still enough characteristically low energy problems to make this field a separate speciality.

- H Hodoscope
- C Chambers
- S Solenoid
- P Photomultipliers
- A Preamplifiers
- L Light guides
- M Magnet Coil
- T Target
- B μ -beam

Fig. 2. SINDRUM apparatus

The first experiment I'll discuss is the SINDRUM² $\mu^+ + e^+e^-e^+$ experiment. A schematic of the apparatus is given in Figure 2. A 'surface' beam³ of $\approx 10^7$ 28 MeV/c muon/sec impinges on a hollow double-cone target. About a quarter of these stop in the target and charged particles from their decays are analyzed in a solenoidal PWC spectrometer ($B = 4\text{kG}$). There are four low-mass cylindrical chambers with resolutions $\sigma_{r-\phi} = .600 \mu$, $\sigma_z = 300 \mu$. A triggering hodoscope outside of the chambers required 3 clusters ($p_{\min}^{\text{TRIG}} \approx 20 \text{ MeV/c}$) while on-line use of the chambers required one negative and two positive tracks, with a total $p_T < 25 \text{ MeV/c}$.

The main backgrounds to $\mu \rightarrow 3e$ are internally or externally converted radiative μ decay $\mu \rightarrow e\nu\gamma$, and normal μ decay in
 $\downarrow$
 e^+e^-
 random coincidence with e^+e^- pairs from radiative decay.

About 250k events were written to tape. The on-line cuts were repeated with one-wire precision and it was found that most 'events' seemed to be two superimposed $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ events one of which spiraled back from the hodoscope to the target region, thus generating a spurious e^- trajectory. Eliminating these and demanding a good vertex in three dimensions left only 52 candidates. Of these only 17 had all three tracks in time ($\sigma_t \approx 350$ psec). Most of the rest had an in-time e^+e^- pair randomly superposed on an e^+ . Figure 3 shows E vs $|\vec{\Sigma p}|$ for in and out of time events. True $\mu \rightarrow 3e$ events would have $|\vec{\Sigma p}| = 0$ and $E = m_\mu$ and thus lie in the semi-circular region shown in the plots. The in-time events populate the region expected for $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu e^+ e^-$ decays. In fact their observed rate and kinematic distribution agree with that predicted for such decays. Since no event consistent with $\mu \rightarrow 3e$ was observed, a 90% confidence level upper limit of $\Gamma(\mu \rightarrow e^+ e^- e^+)/\Gamma(\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu)$ $< 1.6 \times 10^{-10}$ was extracted. This is to be compared with the previous upper limit⁴ of 1.9×10^{-9} . The present data represent only a day or two of running. The ultimate goal of the experiment is a sensitivity of $\approx 10^{-12}$. This certainly seems possible from the statistical point of view. If the reader is tempted to judge from Figure 3(b) whether this will also be true from the point of view of background rejection, keep in mind that the event represented by an open circle is the only survivor of a second, more stringent set of cuts.

In contrast to the SINDRUM apparatus, the Crystal Box experiment⁵ at LAMPF is non-magnetic, seeking to exploit the good energy resolution of NaI. In this way one can gain a factor of ≈ 2.5 in acceptance for $\mu \rightarrow eee$ (8% to 20%), and avoid the complications of a magnetic analysis, at the cost of about a factor 2 in electron energy resolution. In addition, of course, the Crystal Box is sensitive to γ 's, and can search for the decays $\mu \rightarrow e\gamma$ and $\mu \rightarrow e\gamma\gamma$.

Fig. 3. E vs $|\vec{p}|$ for SINDRUM $\mu \rightarrow 3e$ candidates
a) out-of-time events; b) in-time events

Figure 4 shows the apparatus. The Box is composed of 360 $6.3 \times 6.3 \times 30.5$ cm and 36 $6.3 \times 6.3 \times 70$ cm crystals which subtend about 60% of 4π for $\mu \rightarrow e\gamma$ events. The resolution of the NaI is 5.8% FWHM at 50 MeV. Charged particles are tracked in a cylindrical drift chamber ($\sigma \approx 150 \mu$). The experiment seeks to probe the three reactions $\mu \rightarrow e^+e^-e^+$, $\mu \rightarrow e^+\gamma$ and $\mu \rightarrow e^+\gamma\gamma$ to the 10^{-11} level. The present limits on the latter two reactions are 1.9×10^{-9} and 8×10^{-9} respectively^{6,7}.

At the sensitivities being proposed, the poor duty cycle of LAMPF ($\approx 6\%$) is becoming a serious impediment. In the Crystal Box experiment accidentals limit the incident beam rates to $2-5 \times 10^5/\text{sec}$ (average).

The main background to $\mu \rightarrow e\gamma$ stems from random coincidences between e^+ from $\mu \rightarrow e\nu\bar{\nu}$ and γ from $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$. These must be discriminated against via energy, timing, colinearity and target position consistency. A preliminary result is expected within a few months.

Fig. 4. The Crystal Box

Other processes that may be studied by the Crystal Box are $\pi^0 \rightarrow 3\gamma$, $\pi^0 \rightarrow \nu\nu'$, $\pi^0 \rightarrow e^+e^-\gamma$, $\pi^+ \rightarrow e^+\nu_e\gamma$, and $\pi^0 \rightarrow e^+e^-$. There is an approved upgrade⁸ of this experiment in which the NaI is reconfigured into two walls, and a magnetic spectrometer is added. In this way a sensitivity of $< 10^{-12}$ can be reached for $\mu \rightarrow e^+\gamma$.

The last member of this trilogy is the TRIUMF $\mu - e$ conversion experiment.⁹ I remind you that in this case the physics is a little different, basically one has $\mu^- + q \rightarrow e^- + q$ wherein $q = u$ or d . Thus unlike μ decay, both leptons and quarks are involved, and unlike K decay, no strangeness change is required. As a result in many models, this process is predicted to occur at the highest branching ratio of any in which lepton flavor is violated. The

Fig. 5. The TRIUMF TPC

term "branching ratio" for $\mu^- \rightarrow e$ conversion, means the rate relative to that of normal μ capture, i.e., $\mu^- + A \rightarrow \nu_\mu + A'$ in the same material.

The signature for this process is the appearance, in place of a stopped muon, of an unaccompanied electron of unique energy $m_\mu - B$ where B is a small binding energy. The TRIUMF apparatus is shown in Figure 5. It consists of a small TPC¹⁰ augmented by trigger hodoscopes and MWPC's set in a 1T box magnet. The TPC is divided into 6 segments on each end. One readout plane is shown in Fig. 6. Each segment has 12 anode wires which measure the Z position of the tracks to ≈ 1 mm via time-of-flight. These are

Fig. 6. TPC readout of one track

backed up by 6 mm cathode pads which measure the transverse position to $\sim 180 \mu$. This results in a $\Delta p/p$ of $\sim .02$ for 100 MeV/c tracks. The 'cloud' beam provides $10^6 \mu/\text{sec}$ at 77 MeV/c ($\Delta p/p \sim 10\%$, spot size $\sim 10 \text{ cm}$).

An r.f. separator reduces the π contamination in the beam to 10^{-3} , which is essential for reducing background due to radiative π capture. The target which consists of titanium wool, stops some 80% of the beam muons and of these about 85% are captured before they decay. The minority that decay in orbit constitute the most important background to $\mu \rightarrow e$ conversion. This may seem unlikely since electrons from free μ decay never have $E > 53 \text{ MeV}$, and boosts given by atomic orbital velocities are generally small.¹¹ Yet when sensitivities like 10^{-12} are sought, far flung infinitesimally small tails must sometimes be confronted, and in fact, such tails are present in this case. This makes energy resolution crucial.

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Other possible backgrounds are radiative μ capture wherein the γ converts to a very asymmetric pair, radiative pion capture, and cosmic rays. The TRIUMF experiment has been running for some time, and the experimentors are now confident that the proposed sensitivity of $\approx 10^{-12}$ will be reached. This is to be compared with the previous limit¹² of 7×10^{-11} . A preliminary result is expected in a few weeks.

Kaon decays.

It's instructive to compare kaon with muons from the point of view of performing rare decay experiments.

particle	τ	m	possible decay products
μ^+	2197 nsec	$105.6 \text{ MeV}/c^2$	e, γ, ν
K^+	12.4 nsec	$493.7 \text{ MeV}/c^2$	above + $\mu \rightarrow \pi$
K^0	51.8 nsec	$497.8 \text{ MeV}/c^2$	above + K^+

The long lifetime of the μ encourages low energy or stopping beams. The fact that all detectable products are electromagnetic can be exploited to simplify the apparatus as in the case of the Crystal Box. Working at low energy and high rates entails a characteristic set of experimental problems.

By contrast the K^+ lifetime is rather short and it is practical to work even at very high energies, although this has never been done. The availability of intense medium energy beams, the possibility of separated beams and the range of applicability of certain effective particle identification techniques (e.g., gas Cerenkovs) has made 3-10 GeV/c a popular interval. It's also possible to stop large numbers of K^+ 's and a number of experiments have used this technique. One can get relatively pure K^+ beams ($3\pi:1K$ or better) in this way, and the stopping geometry facilitates large acceptance and full veto coverage. There are also rather effective characteristically low energy particle i.d. techniques (e.g., observing the $\pi \rightarrow e$ decay chain in stopped π^+) which lend themselves to this regime. On the other hand, there are

Fig. 7. The Yale-BNL $K_L^0 \rightarrow \mu e$ spectrometer (E780)

also a number of characteristic problems which have to be faced -- for example daughter particle interactions in the stopping target can serve to compromise resolution and particle identification.

For K^0 's there's no stopping option. Rare decay experiments have been performed at just about every other available energy however. Attention is currently focussed on intermediate energy beams. Typically one has a broad bend beam peaked near ≈ 8 GeV/c. To get the highest possible flux one works at 0° production angle and thus must accept a high contamination of neutrons (> 20 n/K).

$$\underline{K_L^0 \rightarrow \mu e}$$

This is a very appealing process from an experimental point of view. Two oppositely charged leptons emanate from a common vertex in a neutral beam. Their maximum p_T is higher than that of any K decay yet observed. There are no uncharged accompanying particles so that the effective mass of the e and the μ equals M_K . The vector sum of the two momenta points back toward the K^0 production target.

The primary background is the copious decay mode $K_L^0 \rightarrow \pi \nu$. If the π is misidentified as a μ the event is topologically equivalent to $K_L^0 \rightarrow \mu e$. If, in addition, the ν carries off very little energy, the event can begin to approach $K_L^0 \rightarrow \mu e$ kinematically as well. Since π 's decay primarily to μ 's, downstream μ identification devices are of limited usefulness. Much more important is good spatial and momentum resolution, both to impose the $K \rightarrow \mu e$ kinematics and to detect possible $\pi \rightarrow \mu \nu$ decays via kinks or other indications. A modern realization of the classic kaon spectrometer used in this work is shown in Figure 7. The K_L^0 are allowed to decay in vacuum and the charged decay products are bent parallel to the beam by a dipole magnet. This permits a relatively large acceptance ($\approx 10\%$ in the pictured spectrometer) and simplifies the trigger. The particle trajectories are measured by high rate (mini) drift chambers and

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the electrons and muons identified respectively by a segmented H_2 Cerenkov counter plus lead glass hodoscope and by a sequence of range-measuring hodoscopes. The electron identification system, which should reject π 's or μ 's by $> 10^5:1$ is probably overkill for the $K \rightarrow \mu e$ mode, but it is useful for possible other physics. The range stack can reject pion punch-throughs to a level at which the background is completely dominated by $\pi \rightarrow \mu \nu$ decay. The limiting background is given by the rare $K \rightarrow \pi \nu$ decays in which the π decays in the middle of the magnet (so the event vertex reconstruction is undisturbed) with its decay plane aligned with the bending plane (so that there is no apparent kink), and with the μ kicked against the sense of the bend (so that the apparent momentum is increased). In addition the neutrino from the original K decay must take off very little energy, so that the event initially is kinematically near enough to the $K \rightarrow \mu e$ for the π momentum mis-measurement to close the gap. One's ability to reject such catastrophic events rises as some power > 2 of the improvement in spatial resolution of the chambers, since the background is distributed over the space of kinematic variables, whereas the target region for true events can be made smaller and smaller. Multiple Coulomb scattering in the chambers finally limits this improvement. In a spectrometer of the dimensions shown here, the chamber resolution corresponding to this limit is about 200μ , which is more or less routinely attainable in modern drift chambers. The residual background level is then reduced to $\approx 10^{-11}$, making practical an experimental sensitivity well beyond 10^{-10} . This is in fact the goal of the Yale-BNL experiment¹³ pictured in Figure 7. To achieve this they will work in a 0° neutral beam containing some $2 \times 10^7 K_L^0$ /pulse (and ≈ 30 times more neutrons). Combining a K_L^0 decay probability of $\approx .012$, and a $K_L^0 \rightarrow \mu e$ acceptance of $\approx .06$, one finds a statistical sensitivity of $0.7 \times 10^{-10}/\text{evt.}$ If the observed chamber rates allow it, the beam will be increased in order to push the sensitivity toward 10^{-11} . This is to be compared

with the present limit¹⁴ of $\approx 10^{-8}$. This experiment will also probe the decay $K_L^0 \rightarrow e^+e^-$ to the same level of sensitivity. Since the standard model expectation for this branching ratio is a few $\times 10^{-12}$, there is a large window, extending from the present upper limit¹⁴ of $\approx 10^{-8}$ down to the ultimate sensitivity of this experiment, in which to look for new physics. Since the large relative suppression of $K_L^0 \rightarrow e^+e^-/K_L^0 \rightarrow \mu^+\mu^-$ in the standard model is due to helicity constraints, this decay mode is particularly sensitive to scalar interactions.

The above experiment is approved and in the process of being built. A second K_L^0 experiment has recently been proposed.¹⁵ It is noteworthy in that its proponents intend to request a primary beam intensity equal to the entire slow extracted beam of the AGS as it is presently operated (10^{13} protons/pulse). It will be used to create a 0° neutral beam. Like the beam of the previous experiment its momentum will peak at about 8 GeV/c and contain a useful K flux from ~ 4 to 20 GeV/c. In addition the beam aperture will be opened to ≈ 100 μ sr. This combination of primary intensity and beam aperture will result in the truly impressive flux of 6×10^8 K_L^0 /pulse. Accompanying them will be the truly daunting flux of $\approx 2 \times 10^{10}$ neutrons/pulse. The apparatus is shown schematically in Figure 8. About 2.2% of the K_L^0 decay in the 6 m vacuum decay region. This is followed by low mass drift chamber spectrometer with two magnets. The acceptance of this device for $K_L^0 \rightarrow \mu e$ is $\approx 6\%$. Electrons are identified by a Ne-Ar Cerenkov counter and by a lead glass wall whereas μ 's are identified in a hadron filter. This combination of decays/pulse and acceptance allows a statistical sensitivity of $\approx 10^{-12}$ (6×10^8 K_L^0 /pulse $\times .022$ decays/pulse $\times 1.2 \times 10^6$ pulses $\times .06$ acceptance/decay $= 1.5 \times 10^{12}$). The anticipated chamber spatial resolution of 100 μ will result in a K mass resolution of ≈ 1.6 MeV/c². Although the resolutions here are comparable to those of the Yale-BNL experiment, the opportunity for a second momentum measurement is

Fig. 8. LANL, Penn, Princeton, Stanford, Temple, UCLA, et al.
 K_L^0 spectrometer (E791)

asserted to allow the $K_L^0 \rightarrow \pi \nu$ background to be reduced by a further factor of 10 or more. This is because μ 's stemming from the 'catastrophic' decay discussed above, emerge from the first section of the spectrometer with a falsely measured momentum. Thus, if no unexpected background processes crop up, the experiment can hope to reach its target sensitivity of 10^{-12} .

The problems connected with such an audacious undertaking should not be underestimated. These are largely consequences of the extremely high rates. The chamber wire spacing is 1 cm with a maximum drift time of 100 nsec. This implies that there will generally be products of at least one extra K_L^0 decay in the chambers in every accepted event. In addition there are the rates due to the 10^{10} neutrons. These are minimized by transporting the neutrons through the center of the apparatus in vacuum, but are still liable to be formidable. Such calculations as have been done

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indicate that the rates will be tolerable but in an experiment of this extreme sensitivity one must worry about higher order effects such as rate-induced degradation of various resolutions. Achieving a manageable trigger rate is no mean task under these conditions. Even after a 10:1 on-line rejection of the principal source of triggers ($K_L^0 \rightarrow \pi \nu$) the fast trigger rate will be

$\downarrow$
 $\rightarrow \mu \nu$

$\sim 10^4/\text{pulse}$. This will have to be beaten down another hundred fold via on-line reconstruction of the decay kinematics.

Although the difficulties are great, so are the possible rewards. In addition to improving the sensitivity on $K_L^0 \rightarrow \mu e$ to 10^{-12} , a very interesting level, the decay $K_L^0 \rightarrow e^+e^-$ should be observable at the standard model rate. In addition the experimentors intend to use their lead glass array to detect γ 's, and thus search for $K_L^0 \rightarrow \pi^0 e \mu$, $\gamma e \mu$, $e^+e^- \gamma$, $\mu^+ \mu^- \gamma$, $\pi^0 e^+e^-$ etc. This last process which has a standard model prediction¹⁶ of $\sim 10^{-11}$ is particularly interesting from the point of view of CP violation. Finally, there is the intention to install a μ polarimeter and measure the μ^+ polarization in $K_L^0 \rightarrow \mu^+ \mu^-$ of which there should be 10^4 examples. It is anticipated that the polarization can be measured to $\sim 14\%$. A signal at this level is equivalent to the detection of a direct CP violating¹⁷ $K_L^0 \rightarrow \mu^+ \mu^-$ decay at the 7×10^{-11} level, a measurement which is otherwise impossible because of the 'large' CP-conserving $K_L^0 \rightarrow \mu^+ \mu^-$ signal.

I'll next discuss the BNL-Washington-Yale $K^+ \rightarrow \pi^+ e^- \mu^+$ experiment.¹⁸ For the same strength interaction $K^+ \rightarrow \pi^+ e \mu$ is some 50 or 100 times less sensitive than $K_L^0 \rightarrow \mu e$ (partly from phase space and partly due to the higher K^+ total decay rate). However, if the lepton flavor violating interaction has no axial vector or pseudoscalar part, the latter reaction is forbidden. Thus both processes must be sought. Another reason for studying $K^+ \rightarrow \pi^+ e^\mp \mu^\pm$ is that one can test the strength of the LFV inter-

action with respect to generation number, an important concept in some models.¹⁹

From an experimental point of view $K^+ \rightarrow \pi^+ e^- \mu^+$ offers a number of advantages. 1) K^+ beams are more tractable than K_L^0 , they can be focussed, bent, etc. In principle, one can make separated K^+ beams (although in practice most often one can't spare the intensity). 2) Because of the relative charged/neutral decay rate one can get four times more K^+ to decay in a given volume than K_L^0 . 3) The K^+ signature beats the K_L^0 , four charged particles to two. 4) There's a 4c fit rather than a 3c fit (this is particularly effective if one can measure the beam momentum). 5) Trigger rate problems for $K^+ \rightarrow \pi^+ e^- \mu^+$ are much less than those of $K_L^0 \rightarrow \mu e$. This can be seen from the following comparison

$$\begin{aligned} \text{leading } K^0 \text{ trigger/decay} &= b(K \rightarrow \pi e \nu) \times (\pi \rightarrow \mu \text{ on line} \\ &\quad \text{misidentification}) \\ &= .39 \times .01 = 4 \times 10^{-3} \end{aligned}$$

$$\begin{aligned} K^+ \text{ trigger/decay} &= b(\pi^+ \pi^0) \times b(\pi^0 \rightarrow \gamma e^+ e^-) \times e \rightarrow \mu \text{ on line} \\ &\quad \text{misidentification}) \\ &= .22 \times .012 \times .01 = 2.5 \times 10^{-5}. \end{aligned}$$

Moreover, this assumes a pessimistic $e \rightarrow \mu$ misidentification. 6) One can gain large factors in background rejection through improvements in particle identification. To be fair I should mention a couple of experimental disadvantages: 1) One has to eat the charged beam (usually mostly π^+ and p) and 2) Particle misidentification can hurt one kinematically in a way which is not possible in $K_L^0 \rightarrow \mu e$. In the latter case if a π from $K_L^0 \rightarrow \pi e \nu$ is misidentified as μ the reconstructed 2-body effective mass will be reduced by the misattribution of the μ mass to the π and the fit to the K_L^0 will be worsened. In the K^+ case there are backgrounds in which this works the opposite way, such as $K^+ \rightarrow \pi^+ \pi^0 \rightarrow \pi^+ e^+ e^- \gamma$ wherein the e^+ is misidentified as a μ^+ . This can raise the reconstructed mass, making up for energy carried off by the photon.

The apparatus of E777 is shown in Figure 9. A 6 GeV beam containing 2×10^7 K^+ , 2.5×10^8 π^+ , and 1.2×10^8 protons/pulse with $\Delta p/p = .1$ impinges on a .11 Λ_K^+ decay tank. Decays are detected in a two-magnet PWC spectrometer (deadened in the beam region). The first magnet kicks the decay products out of the beam and separates them by sign. The second magnet is used for momentum analysis. This arrangement results in a 9% acceptance for $K^+ \rightarrow \pi^+ e^- \mu^+$, and, with a 2 mm PWC pitch, a mass resolution of $\approx 1\%$. The statistical sensitivity is then $[2 \times 10^7 \text{ } K^+/\text{pulse} \times 0.11 \text{ decays}/K^+ \times 10^6 \text{ pulses} \times .09 \text{ acceptances/decay}]^{-1} = 0.5 \times 10^{-11}$.

Each side of the apparatus is specialized to identify particles of its particular sign. On the negative side two H_2 Cerenkov counters in series yield a π or μ rejection of $> 10^5:1$. A shower counter provides a further factor of $> 10^2$ or so. On the positive side two gas Cerenkovs provide a rejection of e^+ by $> 10^4:1$. A somewhat less elaborate shower counter provides a further

Fig. 9. The E777 $K^+ \rightarrow \pi^+ e^- \mu^+$ apparatus

large factor in e^+ rejection. Finally a 7-layer steel-scintillator muon filter serves to reject π^+ punch-throughs by a factor 100.

Unlike the case of $K_L^0 \rightarrow \mu e$, the backgrounds to $K^+ \rightarrow \pi^+ e^- \mu^+$ are quite diverse. I've already mentioned $K^+ \rightarrow \pi^+ \pi^0$ followed by Dalitz decay of the π^0 and subsequent e^+ misidentification as a μ^+ . The decay $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ can produce false $K^+ \rightarrow \pi^+ e^- \mu^+$ candidates in a number of different ways involving various combinations of π decays and misidentifications. There are also potential backgrounds stemming from less common K decays. Table 2, taken from the E777 proposal, lists the most important backgrounds and the (calculated) effects of various background factors. The summed number of residual background events is $< 10^{-11}$, permitting a measurement at this level of sensitivity.

A measurement at the 10^{-11} level represents a 500-fold improvement on the present upper limit²⁰ for the branching ratio for $K^+ \rightarrow \pi^+ e^- \mu^+$. In addition the experiment should be able to collect several thousand examples of the rare decay $K^+ \rightarrow \pi^+ e^+ e^-$ for which the present world supply is some 30 events.²¹ This process is interesting both because of the light it sheds on higher order electroweak processes in the standard model and because of the opportunity it affords to search for decidedly non-standard states decaying into $e^+ e^-$. Another possible by-product of this experiment is a clean high-statistics measurement of the decay $\pi^0 \rightarrow e^+ e^-$. $K^+ \rightarrow \pi^+ \pi^0$ provides a 'tagged' π^0 for this purpose. This process, which has been measured in two experiments²², appears at a rate significantly in excess of the standard model prediction.²³

The third kaon decay experiment I'll discuss is $K^+ \rightarrow \pi^+ + X^0$ where X^0 denotes an undetectible neutral particle or particles. In the case that the X^0 is a neutrino-antineutrino pair, this process has a significant standard model rate. However, this branching ratio is small enough, $O(10^{-10})$, in relation to the present upper limit²⁴ of 1.4×10^{-7} , to allow a very large window for the observation of possible new physics. The lack of significant long

distance contributions to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ makes this process, unlike $K_L^0 \rightarrow \mu^+ \mu^-$ or $K^0 \leftrightarrow \bar{K}^0$ mixing, a clean test of higher order corrections in the standard model. Figure 10 shows the diagrams involved. The prediction depends only on K-M matrix parameters and on quark masses, the principle unknowns at the moment being the CP violating phase δ , and the top quark mass. Recent determinations of the b-quark lifetime²⁵ have narrowed the range of prediction considerably, as shown by Fig. 11 which is taken from a recent paper of Gilman and Hagelin.²⁶ For a top quark mass of 100 GeV/c, the branching ratio is predicted to be between 6×10^{-11} and 6×10^{-10} , assuming 3 generations of light neutrinos. Future progress in determining the parameters of the 6 quark model can only help in making the prediction more precise. On the other hand, if this progress is stalled a measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ rate can provide a valuable constraint on these parameters, as well as a check on the overall consistency of the standard model.

Fig. 10. Standard model contributions to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Fig. 11. Branching ratio limits on $K^+ \rightarrow \pi^+ \nu_i \bar{\nu}_i$ vs M_t .
(from Gilman and Hagelin²⁶). Measured rate
will be 3 times this.

If on the other hand the measurement falls significantly outside the 6 quark model bounds, it would constitute a clear signal of new physics. The possibilities for this are numerous and diverse. As discussed by Ellis and Hagelin²⁷ and Kane and Shrock²⁸ a fourth generation of quarks and leptons could either

subtract or add to the branching ratio. It's possible that lepton flavor-violating interactions could contribute, giving decays like $K^+ \rightarrow \pi^+ \nu_e \bar{\nu}_\mu$ etc., although clearly this process is not the best probe of such physics. There are a number of possible supersymmetric contributions, some of which are shown in Figure 12. Again there are possibilities for either constructive or destructive interference depending on the various masses and mixings. One interesting possibility is the tree level contribution²⁹ shown in Figure 12(h) which could give a contribution almost as large as the present experimental upper limit. Finally, there is also the possibility of contributions as yet undreamt of in our philosophy.

Fig. 12. A selection of possible supersymmetric contributions to $K^+ \rightarrow \pi^+ X^0$.

The decay $K^+ \rightarrow \pi^+ X^0$ when X^0 is a single unobserved particle is also extremely interesting. Although the conventional axion is dead, Wilczek has introduced a successor called the familon.³⁰ This is the Goldstone boson of a hypothesized family symmetry breaking whose scale F is in the 10^{12} GeV region. The predicted branching ratio is $b(K^+ \rightarrow \pi^+ f) \approx 2.75 \times 10^{13} \text{ GeV}^2/F^2$. Cosmological constraints limit F to between 10^9 and 10^{12} GeV, and thus $b(K^+ \rightarrow \pi^+ f^0)$ to 2.75×10^{-5} to 2.75×10^{-11} . Other possibilities also exist for X^0 .³¹

Although the motivation to search for $K \rightarrow \pi^+ + X^0$ is strong, the experimental difficulties are considerable, particularly in the case when X^0 is a two particle system. Unlike the other K decays discussed, there is no strong kinematic signature. It's necessary to veto any charged particles or γ 's accompanying the final state pion, and excellent particle identification is needed to establish that it is indeed a pion. Yet the target branching ratio, $\approx 10^{-10}$, is not so much higher than that of the lepton flavor violation experiments discussed above.

All searches for these decays past and present have used a stopping K^+ beam. One is then working directly in the center of mass system and can use kinematics at least to veto certain background reactions. Figure 13 illustrates the kinematical situation. It gives the distribution in range³² in scintillator of the charged products of various relevant K^+ decay modes. The π^+ from $K^+ \rightarrow \pi^+ \bar{\nu} \nu$ has a typical vector spectrum peaking near its maximum range. The two largest K^+ branching ratios, $K^+ \rightarrow \mu^+ \nu$ (63.5%) and $K^+ \rightarrow \pi^+ \pi^0$ (21.2%) appear as spikes at about 58 and 32 g/cm² respectively. The spikes are shown broadened by a range resolution of $\approx 1 \text{ g/cm}^2$. Note that no known K^+ decay mode produces a π^+ with a range larger than that of $K^+ \rightarrow \pi^+ \pi^0$. Thus, in principle, any K^+ decay producing a daughter π^+ with a range exceeding that of $\pi^+ \pi^0$ must³³ be a $K^+ \rightarrow \pi^+ \bar{\nu} \nu$. This has led most

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previous experiments to concentrate on the region of phase space above the $\pi^+\pi^0$, at a cost of about a factor 5 in acceptance. In the past the primary residual background was due to $K^+ \rightarrow \mu^+\nu\gamma$ which has a branching ratio of $\approx 6 \times 10^{-3}$. The γ is difficult to veto since it has little energy and tends to follow the μ^+ . Since the μ^+ range distribution from this reaction straddles the region of $\pi^+\bar{\nu}\nu$ acceptance, one needs excellent μ^+ rejection to reduce this background to an acceptable level.

The apparatus of AGS experiment 787³⁴ is shown in Figure 14. An 800 MeV/c separated K^+ beam of $\approx 350,000/\text{pulse}$ is degraded to ≈ 350 MeV/c in a barium fluoride scintillator and brought to rest in a live stopping target. This will consist of a bundle of scintillating fibers which provide a detailed picture of the K^+ stop and subsequent decay. Surrounding the target is a cylindrical drift chamber which covers about 50% of 4π . A large iron bound solenoid enclosing the apparatus provides a 1T field, allowing $\approx 2\%$ momentum measurement on the π^+ . Outside the drift chamber is a cylindrical array of range counters about 40 cm thick. These counters serve to distinguish charged pions from muons or electrons in a number of different ways. They make possible measurements of both the range and the energy of the stopping pions. Comparison of these quantities with the measured momentum yields a relative μ rejection of $> 2 \times 10^4:1$. Observation of the $\pi \rightarrow \mu \rightarrow e$ decay chain in the stopping counter yields a further factor $\geq 10^5:1$ against muons. This technique works so well, in spite of the large ambient rates, because of the high effective segmentation of the stopping counters. This is achieved by reading out the range counters on two ends, making possible a determination of the various signal sources to a few cm by means of differential timing and pulse height measurements. Thus one can require that all three signals emanate from the same area of the stopping counter.

Fig. 13. Range distribution of final state charged particle from various K^+ decay modes.

Surrounding the range stack is an array of lead-scintillator "barrel" counters. The use of very thin (< 1 mm) Pb plates allows a sufficiently low threshold (≈ 20 MeV) for efficient vetoing of background γ 's. This veto coverage is completed by inserting 1 mm lead sheets between the range counters (outside the π acceptance region) to make the end regions of the range array into shower counters and by the use of barium fluoride scintillators in the forward and backward regions. BaF_2 (radiation length ≈ 2 cm), has a fast scintillation component with decay time ≈ 0.6 nsec so that it can cope with the high rates of the beam region. It will be read out via low pressure PWC's doped with TMAE.³⁵

Fig. 14(a). E787 Apparatus (Side View)

The combination of μ rejection and γ vetoing reduces the $K^+ \rightarrow \mu^+ \nu \gamma$ background to a level below that of other processes. In fact the leading residual background is likely to be one of two processes neither of which is a K^+ decay. One is simply a large angle scattering of a beam π^+ . In order to defeat the trigger this must occur within about 50 nsec of a stopping K^+ which happens to decay very late. The segmented target will afford some protection against this, but the primary line of defense is the introduction of veto Cerenkov counters and scintillator hodoscopes into the beam. The second potential background is due to K^+ charge exchange in the stopping target. If this occurs at low enough energy the resulting K_L^0 may be soft enough to remain in the target beyond the end of the stopping gate delay. It can then decay semi-lep-

tonically--occasionally giving the lepton so little energy that it is lost in the target. This is calculated to give a residual background of $\leq 2 \times 10^{-11}$.

The sensitivity of the experiment is $\approx 2.3 [3.5 \times 10^5 \text{ stops/pulse} \times 2 \times 10^6 \text{ pulses} \times .015 \text{ acceptance}]^{-1} = 2 \times 10^{-10}$. This is low enough to be sensitive to the entire window between the current upper limit of 1.4×10^{-7} and the standard model prediction of $\approx 10^{-10}$. Since the acceptance for $K^+ \rightarrow \pi^+ f$ is five times greater than that for $K^+ \rightarrow \pi^+ \bar{\nu}$, the sensitivity for this decay will be at the 4×10^{-11} level. This permits almost the entire allowed range of the family symmetry scale F to be probed.

Fig. 14(b). E787 Apparatus (End View)

Fig. 15, Current and anticipate branching ratio limits for rare decays

In addition there are many other interesting decay modes which can be studied with this apparatus. The complimentary decay to that of E777, $K^+ \rightarrow \pi^+ e^+ \mu^-$ can be probed down to $\approx 7 \times 10^{-11}$. The neutral current decay $K^+ \rightarrow \pi^+ \gamma \gamma$ ought to be observed (the standard model prediction is $\approx 10^{-7}$). One can tag π^0 's via the decay $K^+ \rightarrow \pi^+ \pi^0$ and search for $\pi^0 \rightarrow$ 'nothing'. Other less exotic but still interesting K^+ decays such as $K^+ \rightarrow e^+ \nu \gamma$ and $\mu^+ \nu \gamma$ can also be studied.

Figure 15 shows the current and anticipated future experimental situation for the processes discussed above.

In the next few years rare decay experiments should provide stringent tests of the standard model. Limits on lepton flavor violating processes will be pushed down to levels of 10^{-11} - 10^{-12} which correspond to new physics scales in the tens or hundreds of TeV. A number of K decays like $K_L^0 \rightarrow e^+ e^-$, $\pi^0 e^+ e^-$, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, etc., will be probed down to or near the level of the highly suppressed standard model contribution, affording large windows for new physics.

Useful discussions with D. Bryman, L-L. Chau, R. Cousins, F. Gilman, J. Hagelin, C.M. Hoffman, G. Kane, W-Y. Keung, W. Marciano, W. Molzon, W. Morse, M. Schmidt, R. Shrock, H.K. Walter, S. Wojcicki, and M. Zeller are gratefully acknowledged.

This work was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

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TABLE I
RELATIVE SENSITIVITIES OF LFV PROCESSES

Processes	Multiple Higgs	PS LQ	V LQ	U(1) HGB	SU(2) HGB	Exp BR $\times 10^{10}$
$B(\mu \rightarrow e\gamma)$	.011	—	—	*	130	1.9
$B(\mu \rightarrow e\bar{e}e)$	.040	—	—	89	270	1.6
$B(\mu Z \rightarrow eZ)$	.35	.140	550	251	940	0.7
$B(K_L^0 \rightarrow e\mu)$	.90	.38	197	237	76(0)	100
$B(K^+ \rightarrow \pi^+ \mu e)$	.12	.03	10	69	47(94)	50

Mass limits in TeV

For branching ratio upper limit of 10^{-10}

$$M_{\text{heavy}} \propto (\text{BR})^{-1/4}$$

Mode	Evt. Gen.	Total Decays	Signal Events	Bkg Level	x Misident as y	Misident Prob	Final Bkg Level ($\times 10^{-12}$)	Comment
$\pi^+\pi^+\pi^-$	2.5×10^4	4×10^5	0	2.7×10^{-5}	π^- as e^- π^+ as μ^+	2×10^{-7}	<5.4	No events with M_K greater than 445 MeV
$\pi^+\pi^+\pi^-$ $\mu^- \nu$	10^5	1.6×10^7	37	2.5×10^{-5}	μ^- as e^- π^+ as μ^+	2×10^{-8}	0.5	
$\pi^+\pi^+\pi^-$ $\mu^+ \nu$	10^4	0.9×10^6	3	3×10^{-5}	π^- as e^-	10^{-7}	3	
$\pi^+\pi^+\pi^-$ $e^- \nu$	1.4×10^5	10^{12}	1	1×10^{-11}	π^+ as μ^+	10	<.13	Forshortened decay length of π by 50
$\pi^+\pi^+\pi^-$ $\mu^- \nu$ $\mu^+ \nu$	10^4	8×10^7	0	$<1.3 \times 10^{-6}$	μ^- as e^-	10^{-7}	<0.1	
$\pi^+\pi^+\pi^-$ $e^- \nu$ $\mu^+ \nu$	10^5	1.8×10^{13}	1	0.6×10^{-12}	π^- as e^-	$<10^{-2}$	<0.1	Only good event π^- decayed beyond CLR.
$\pi^0 \mu^+ \nu$ $e^+ e^- \gamma$	2.5×10^4	0.6×10^8	0	$<1.8 \times 10^{-7}$	e^+ as π^+	10^{-6}	<0.18	
$\pi^0 \pi^+$ $e^+ e^- \gamma$	2.5×10^4	10^7	1	1.1×10^{-5}	e^+ as μ^+	10^{-5}	1.1	