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Rare Kaon, Muon, and Pion Decay

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ABSTRACT

I discuss the status of and prospects for the study of rare decays of kaons, muons, and pions.

1 Introduction

Studies of rare K and μ decays are quite active at the present time and have very interesting future prospects. The area of pion decay is less active, with most recent results being parasitic on K experiments.

2 Rare K Decay

2.1 $K \to \pi\nu\bar{\nu}$

At present the rare K decays on which most interest is focussed are the charged and neutral versions of $K \to \pi\nu\bar{\nu}$. In the Standard Model (SM), these are sensitive to respectively the modulus and the imaginary part of the Cabbibo-Kobayashi-Maskawa (CKM) element V_{td}. The branching ratios can be written in terms of the very well-measured rate of K_{e3}, eliminating the otherwise problematical hadronic matrix element. Isospin breaking corrections to this relation are small and very well determined [1]. QCD corrections have been carried out to next-to-leading-logarithmic-order [2], and the residual uncertainty is at the few percent level for the charged channel, and $< 2\%$ for the neutral. Possible long distance effects have

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been investigated for both the charged [3] and neutral [4] channels and found to be negligible. Thus it is possible to make rather precise SM predictions for these decays [2, 5] in terms of parameters such as m_t, $|V_{td}|$ and $|V_{cb}|$. In principle, one could extract $|V_{td}|$ to around 5% from a measurement of $B(K^+ \to \pi^+\nu\bar{\nu})$, and η to about 1% from a measurement of $B(K_L \to \pi^0\nu\bar{\nu})$. Fig.1 shows the relationship of these decays to the unitarity triangle, and a comparison with the standard one from B decays. Recently there has been much theoretical work on the effects of non-SM physics on these decays. Predictions have been made in two-Higgs doublet models [6], a four-generation scenario [7], left-right models [8], leptoquark models [9], and several variants of supersymmetry [10]. It is found that such new physics tends to affect the K sector quite differently than the B sector. Thus the motivation for pursuing these modes is extremely strong and is likely to remain so for quite a while

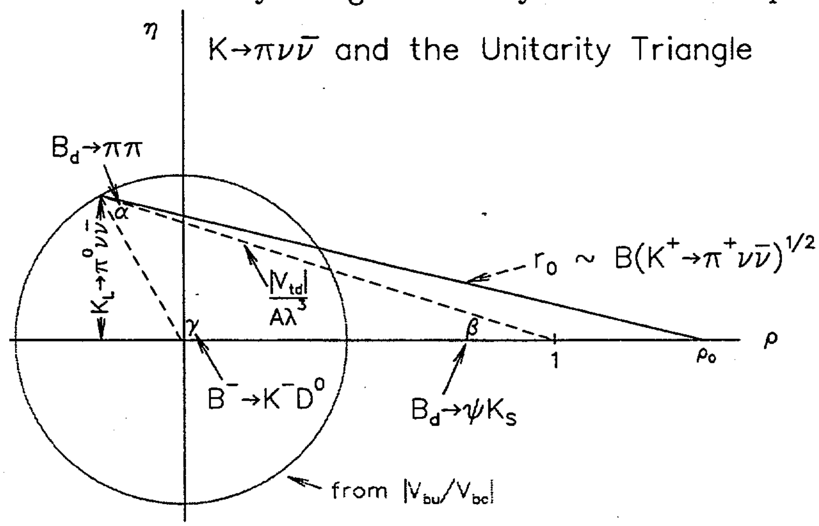


Figure 1: *Diagram of the contribution of the charged and neutral FCNC kaon decay* $K \to \pi\nu\bar{\nu}$.

However the measurements are not easy. The branching ratios predicted by the Standard Model are $(0.6-1.5)\times10^{-10}$ for the charged and $(1-3)\times10^{-11}$ for the neutral decay and the signatures for these processes are rather poor. Pions are very common decay products of kaons, and the unobservable $\nu\bar{\nu}$ pair insures that there is at best a very weak kinematic signature. One must prove a negative, *i.e.* that there was a pion from kaon decay that was unaccompanied by any other visible particles. To do this at the level of a part in ten billion is a real challenge.

2.1.1 $K^+ \to \pi^+\nu\bar{\nu}$

Brookhaven AGS-787 has been pursuing the charged mode for several years. Fig. 2 shows the detector, a highly instrumented solenoidal spectrometer [11] situated at the end of a 700 MeV/c separated beamline. It provides a $\sim$ 75% pure beam of $\sim$ 6 million K^+ per AGS spill, of which about 1.5 million stop and decay in a

400-element scintillating stopping target. Daughter pions are momentum analyzed in a small foil-cathode drift chamber [12] in a 1-T field, and subsequently come to rest in a cylindrical array of scintillators and straw chambers (the "range stack"). They are distinguished kinematically from muons by comparing their range, energy, and momentum, and also by their characteristic decay pattern after coming to rest ($\pi \to \mu \to e$). The range stack is surrounded by a cylindrical lead-scintillator photon veto array, and the upstream and downstream faces of the detector are plugged with CsI-pure endcap vetoes [13].

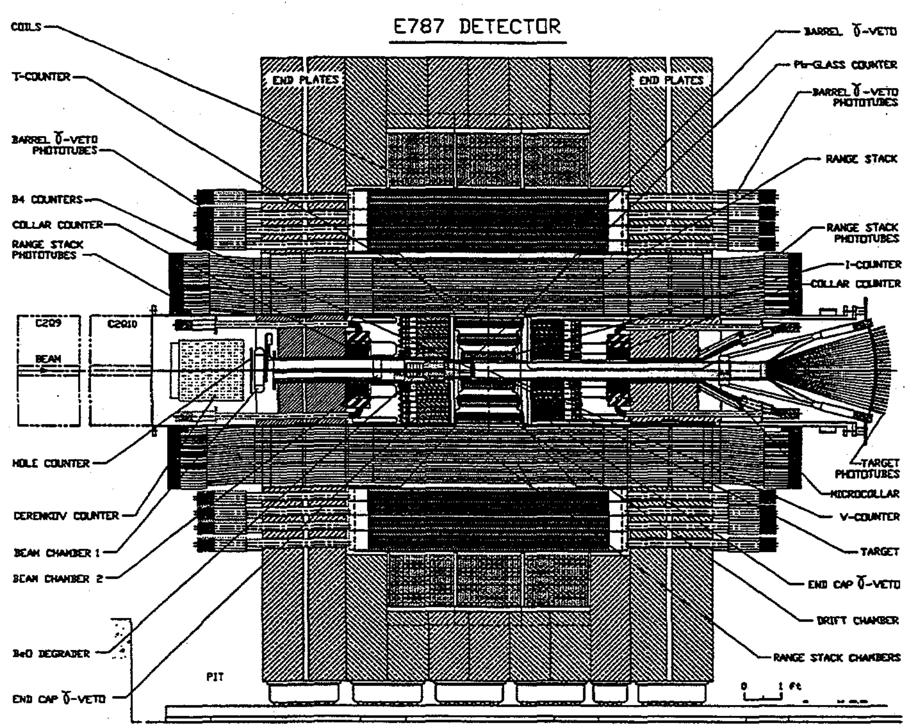


Figure 2: *Schematic of AGS-787 detector.*

The E787 experiment in its present form has been taking data since 1995. A very convincing $K^+ \to \pi^+\nu\bar{\nu}$ event was discovered in an initial analysis of the 1995 data [14], yielding a branching ratio of $B(K^+ \to \pi^+\nu\bar{\nu}) = (4.2^{+9.7}_{-3.5}) \times 10^{-10}$. This is consistent within statistics with the SM estimate, but 3−4 times higher. The 1995-7 data set should yield a sensitivity at least 2.5 times greater, and a long run is scheduled to begin in the summer of 1998. This should confirm or eliminate the possibility of a large violation of the SM in this mode. The estimated background in the analysis that yielded the event corresponds to about 4×10^{-11}. This is within shooting distance of the level of background suppression needed for making an accurate measurement at the SM level. Thus it appears possible to exploit this very challenging reaction to study short distance effects whether SM or non-SM.

Elements of the E787 collaboration are interested in pursuing this physics to the next order of magnitude in sensitivity [15]. Straightforward optimization of the running conditions (proton supply, beam momentum, duty cycle) along with machine availability expected in the RHIC era would allow a sensitivity of ~ 2.5 SM events/year without big improvements in the detector. Reasonable upgrades might allow this to be doubled. Thus $10-15$ events at the SM level seem attainable.

To get still a further factor 10, the CKM experiment has recently been proposed [16] the Fermilab Main Injector (FMI). Fig 3 shows the proposed detector.

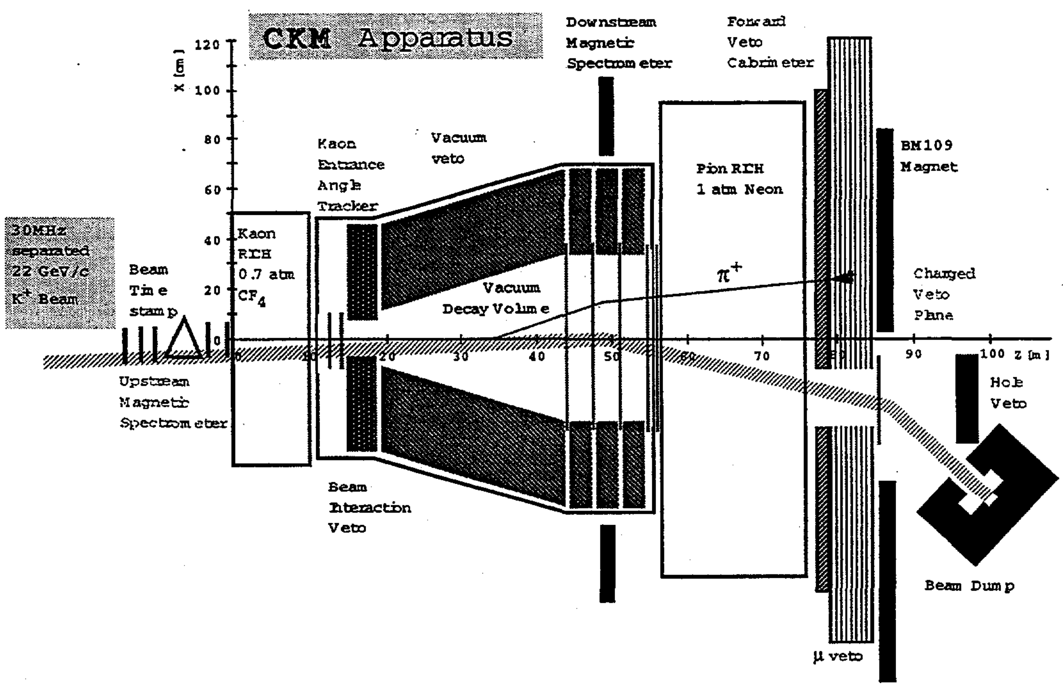


Figure 3: *Schematic of the CKM detector.*

It represents a completely orthogonal approach to that of E787 - the experiment is done in flight at a K^+ momentum of ~ 22 GeV/c. This requires a new RF-separated beam. The experiment features phototube read-out RICHs for identification of K^+ and π^+ and measurement of their velocities, as well as momentum analysis, hermetic photon vetoing, and a crude hadronic calorimeter used as a muon veto. Many other decay modes could also be studied by this detector.

2.1.2 $K_L \to \pi^0 \nu \bar{\nu}$

It was pointed out several years ago that this reaction offers a uniquely incisive window into the question of CP-violation in the K system [17]. However until very recently no experiment has been dedicated primarily to its study. The best sensitivity thus far stems from a one-day test run of the KTeV experiment at FNAL [18] (see Fig. 4). They obtained an upper limit of $B(K_L \to \pi^0 \nu \bar{\nu}) < 1.6 \times 10^{-6}$ at 90% c.l. [19]. This experiment is expected to eventually reach the 10^{-8} level. Since in the SM a measurement is expected to require better than 10^{-11}/event sensitivity, one has a long way to go. However there are three initiatives for dedicated experiments to close this gap.

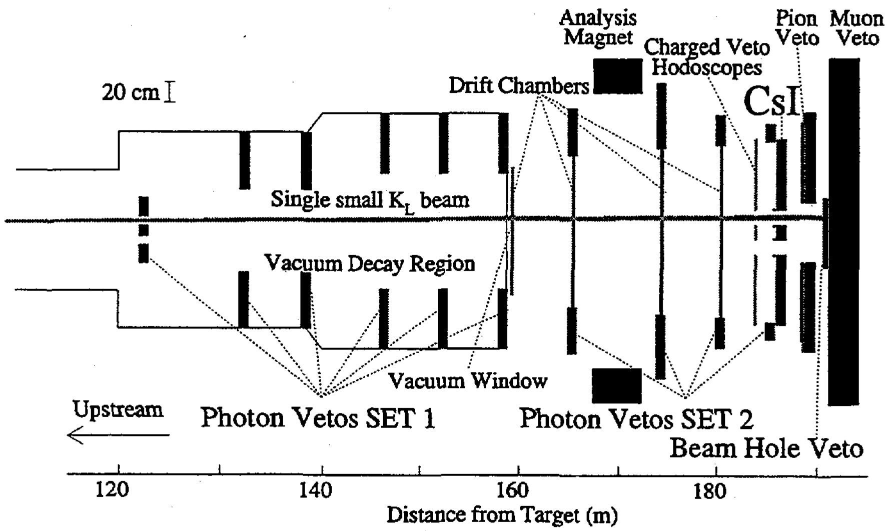


Figure 4: *Schematic of the KTeV detector as configured for special $K_L \to \pi^0 \nu\bar{\nu}$ run.*

BNL AGS-926 [21] exploits the advantages of working at very low kaon momentum. A conceptual apparatus is shown in Fig. 5. A K_L beam of average momentum $\sim 750\,\mathrm{MeV/c}$ can be obtained from a 24 GeV primary by using a very large production angle. The accelerator beam can be microbunched on extraction [22], allowing the velocity of the K_L to be measured by time of flight. The microbunching also makes the experiment insensitive to much of the rates and potential backgrounds stemming from neutrons in the beam. The decay vertex can be determined by measuring the directions as well as the energies of the π^0 γ's. Since the production point of the K_L is thereby known, this determines the K_L direction. The direction and the velocity determine the momentum, so that one can transform into the K_L c.m. In this system, π^0's from the main background reaction, $K_L \to \pi^0\pi^0$, have a unique energy, and can thus be kinematically rejected. This reduces the need for an otherwise very challenging level of photon vetoing power ($K_L \to \pi^0\pi^0$ is some 8 orders of magnitude more copious than $K_L \to \pi^0\nu\bar{\nu}$). Other advantages of working at low energy are the possibility of a relatively compact detector, the low probability for a beam neutron to create a π^0, and the suppression of background from hyperon decay. The experiment aims to collect some 70 events with a 10 : 1 signal/background ratio in three years of running.

The KAMI approach to probing $K_L \to \pi^0\nu\bar{\nu}$ [23] exploits the very high proton current projected to be available at the Fermilab Main Injector (FMI) to make a reasonably intense narrow K_L beam. The present KTeV CsI electromagnetic calorimeter would remain the heart of the detector, but, as shown in Fig. 6, the apparatus would be telescoped to match the lower beam energy (120 GeV vs 800

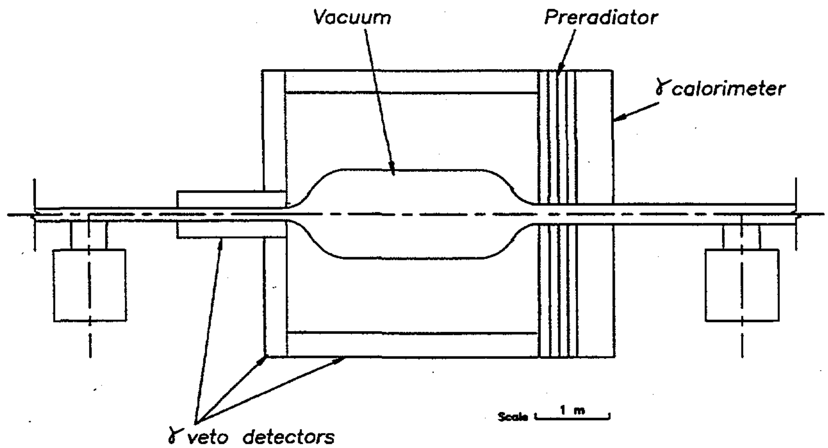


Figure 5: *Schematic of the proposed BNL AGS E926 detector for* $K_L \to \pi^0 \nu \bar{\nu}$.

GeV). This would allow a relatively high acceptance ($\sim 7\%$), moderating the need for an extremely high K_L flux. The present photon veto system would be replaced by a more nearly hermetic one. One of the main challenges of this approach is the need for extremely good photon vetoing efficiency. This must get into the ballpark of 10^{-6}/photon inefficiency for some photons, and, for high energy photons, needs to be better than 10^{-2} even in the beam. The requirement of photon vetoing can be relaxed by tightening the $\pi^0\, p_T$ cut, but at a substantial cost in acceptance. If this should not prove to be necessary, the first stage of the experiment would collect about 30 events/year with a $2:1$ signal/background. The goal of the second stage, in which the production target is moved closer to the detector, is to collect 124 events/year with a $3:1$ signal/background ratio.

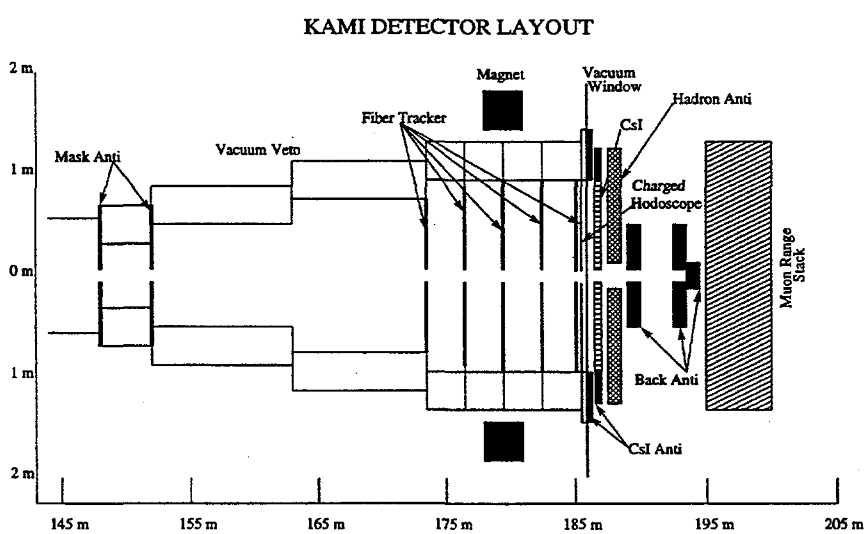


Figure 6: *Schematic of the proposed KAMI detector for* $K_L \to \pi^0 \nu \bar{\nu}$.

The first dedicated $K_L \to \pi^0 \nu \bar{\nu}$ experiment is KEK E391a [24]. It is similar in concept to the KAMI approach, but optimized for five times lower energy (see Fig. 7). E391a features a very carefully designed pencil beam, an hermetic photon veto system and crystal photon detectors. Very high single-photon efficiency is required to suppress the $K_L \to \pi^0\pi^0$ background, and tagged photon studies of this are in progress at the INS-ES. As in all attempts to detect $K_L \to \pi^0\nu\bar{\nu}$, a high vacuum is needed in the beam region to minimize π^0 production from neutrons. In this case, virtually the entire apparatus is in vacuum. An outer chamber provides 10^{-3} Torr, and an inner chamber 10^{-7} Torr. The acceptance of the detector is designed to be $\sim 7\%$, similar to the case of KAMI. The beam intensity available at the KEK PS is insufficient to get beyond a sensitivity of 10^{-10}/event, *i.e.* not enough to see this decay mode if the Standard Model is correct. However, the experiment will serve as a test bed for a very similar effort at the planned Japanese Hadron Facility (JHF) where the intensity is sufficient to get a great many events with a detector of this acceptance.

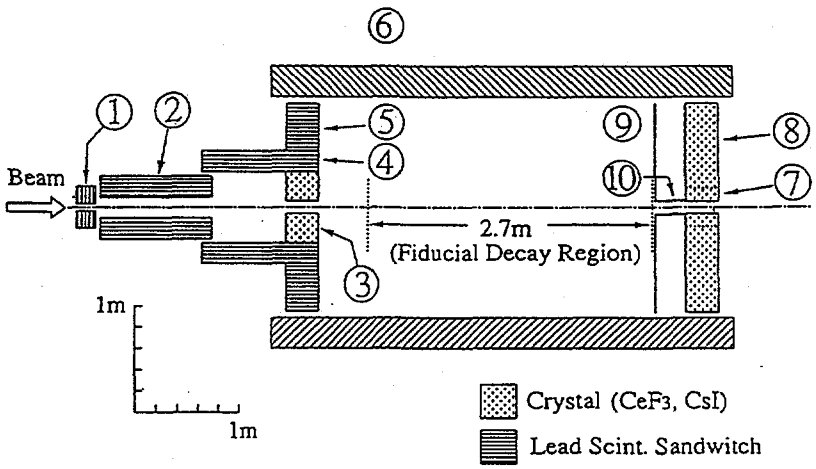


Figure 7: *Schematic of the KEK-391a detector for* $K_L \to \pi^0\nu\bar{\nu}$.

2.2 $K_L \to$ two charged leptons

AGS-871, a search for $K_L \to \mu e$, $K_L \to \mu^+\mu^-$, and $K_L \to e^+e^-$, is the most sensitive K decay experiment yet carried out. The experimenters deployed a modern update of the classic two-body K^0 decay spectrometer in a beam of $\sim 10^8$ K_L/spill.

This experiment has recently announced a new result on $K_L \to \mu e$ [25]. They find that the branching ratio for this lepton flavor-violating decay is less than 5.1×10^{-12} at 90% c.l. Assuming electroweak-strength couplings, this corresponds to a scale of > 100 TeV for the mass of a hypothetical horizontal gauge boson that could mediate this decay [26]. Using this result, bounds can also be put on various types of leptoquarks [9], and other BSM entities [27].

This group has also recently announced a preliminary result on $K_L \to \mu^+\mu^-$ [25]: $B(K_L \to \mu^+\mu^-) = (7.23 \pm 0.22) \times 10^{-9}$, based on a sample of more than

6200 events(see Fig. 8). This result should be compared with the "unitarity bound" of $(6.83 \pm 0.30) \times 10^{-9}$. The latter is the contribution to $K_L \to \mu^+\mu^-$ from an intermediate $K_L \to \gamma\gamma$ decay. The bound is the absorptive part of this contribution and is extremely well-determined theoretically (its uncertainty is dominated by the experimental error on $B(K_L \to \gamma\gamma)$). There is also a rather less well-determined dispersive contribution, which has been the subject of much theoretical effort [28]. It would be quite desirable to settle this question since there is also a short-distance contribution to the real part of the amplitude for $K_L \to \mu^+\mu^-$. It arises from loops very much like those that mediate $K \to \pi\nu\bar{\nu}$, and is sensitive to the CKM parameter ρ. The final result of this experiment is expected to have a 2% error which is a very interesting level if the theoretical issues can be resolved.

The closely related process $K_L \to e^+e^-$ has also been studied by this group. They have recently announced the first observation of this decay [25], with a branching ratio of $(9.4^{+5.9}_{-4.6}) \times 10^{-12}$. The kinematics of the four events on which the result is based are shown in Fig 9. The measured branching ratio agrees well with the theoretical predictions [28], closing a window on possible contributions of non-SM pseudoscalar currents to this decay.

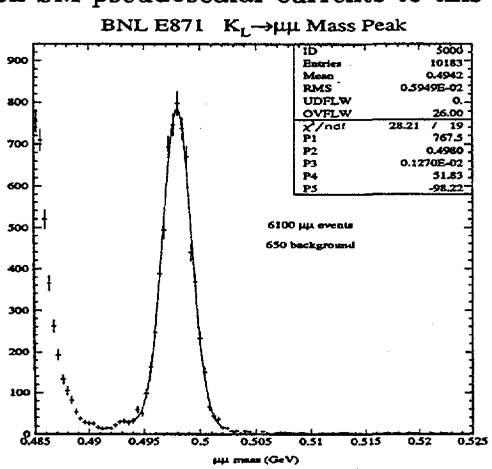


Figure 8: $K_L \to \mu^+\mu^-$ candidates from AGS-871.

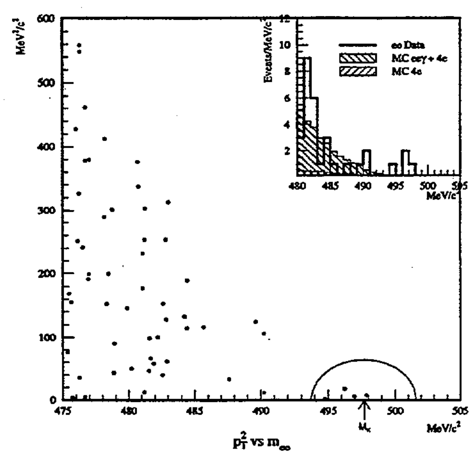


Figure 9: p_T^2 *vs* m_{ee} *for* $K_L \to e^+e^-$ *candidates from AGS-871. Signal region is near* $p_T^2 = 0$ *and* $m_{ee} = m_K$.

2.3 Other multi-body K decays

There is also an experiment at BNL, AGS-865, to search for a second lepton flavor-violating process, $K^+ \to \pi^+\mu^+e^-$. If the new current is a vector, for example, this process can occur while $K_L \to \mu e$ cannot. E865 is collecting data with the aim of reaching a single event sensitivity of $\sim 5 \times 10^{-12}$ by 1999, but they do not have a recent result on $K^+ \to \pi^+\mu^+e^-$. They do have results on several other processes, however. They now have $10,000$ $K^+ \to \pi^+e^+e^-$ and 400 $K^+ \to \pi^+\mu^+\mu^-$ events (see

Fig 10). There's a well known relation between the branching ratio and the spectrum shape predicted [29] by Chiral Perturbation Theory (χPT), that now seems to be badly violated in the electronic version of this decay. The data is in the process of further analysis, and it appears that it will pose a significant challenge to theory.

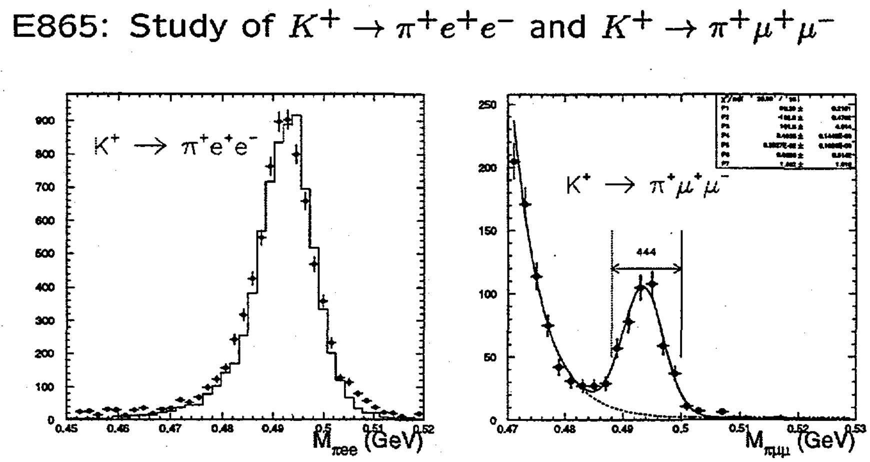


Figure 10: *Mass spectra of* $K^+ \to \pi^+e^+e^-$ *and* $K^+ \to \pi^+\mu^+\mu^-$ *candidates from AGS-865.*

E865 also has large data sets of previously poorly known decays such as $K^+ \to \mu^+\nu e^+e^-$ and $K^+ \to e^+\nu e^+e^-$, which should provide further critical tests of χPT. In addition they have collected large data sets of $K^+ \to \pi^+\pi^-e^+\nu$ and $K^+ \to \pi^0e^+\nu$. The former is important in the determination of low energy $\pi - \pi$ phase shifts and the latter will contribute toward a better measurement of the CKM matrix element V_{us}.

The KEK-162 and the KTeV experiments have observed the decay mode $K_L \to \pi^+\pi^-e^+e^-$. The latter now have a preliminary branching ratio of $(3.32 \pm 0.14 \pm 0.28) \times 10^{-7}$ based on about 3000 events [30]. This data will be interesting when fully analyzed because it is likely to show a sizable CP-violating effect in the distribution of the angle between the $\pi^+\pi^-$ and e^+e^- planes in the K_L center of mass frame [31]. Although this is expected to be purely a state-mixing effect, it will be the first example of CP-violation in a dynamical quantity.

3 Rare Muon Decays

In the minimal Standard Model, lepton flavor conservation is built in by hand with the assumption of vanishing neutrino masses. In fact, virtually any new physics or interaction beyond the Standard Model would predict lepton flavor violation (LFV) at some level. The LFV K-decays discussed above have gone somewhat out of fashion, and the LFV processes of major current interest are those with muons such as $\mu^+ \to e^+\gamma$ and $\mu^-N \to e^-N$ conversion in nuclei. Historical progress in various LFV searches is shown in Fig.11, in which the experimental upper limits have been continuously improved at a rate of about two orders of magnitude per decade for about 50 years since the first LFV experiment by Pontecorvo et al. in 1947 [32]. In general, a search for $\mu^+ \to e^+\gamma$ with a branching ratio sensitivity of about 10^{-12} explores a mass scale of several hundred TeV, something which is not accessible directly by present or near-future accelerators.

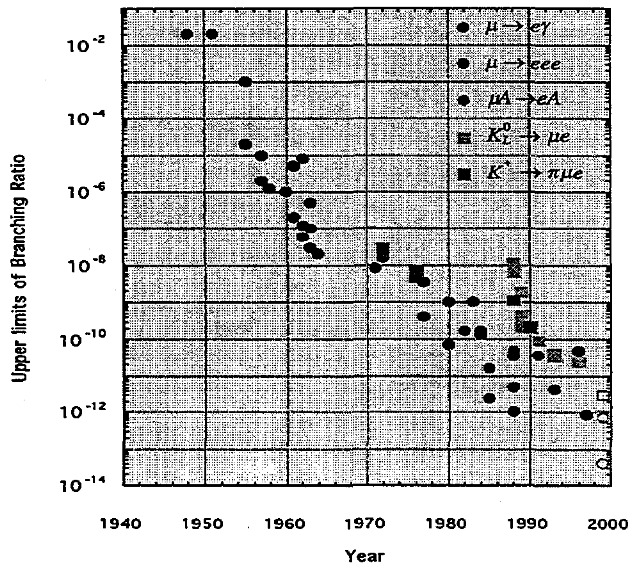
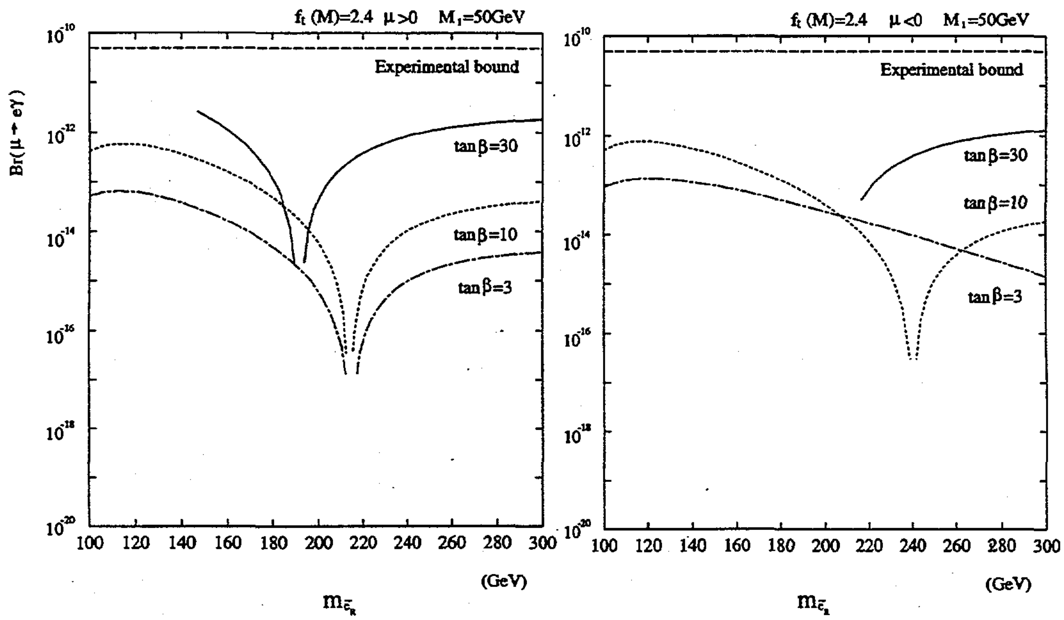


Figure 11: *History of LFV searches for various processes of kaons and muons.*

Recently considerable interest in muon LFV processes has arisen based on supersymmetric extensions to the Standard Model, in particular supersymmetric grand unified theories (SUSY-GUTs) [33]. In many models of SUSY-GUT, LFV can be naturally introduced. For instance, in supergravity-mediated SUSY models, radiative corrections in the renormalization group evolution from the GUT scale to the weak scale lead to finite mixing in the slepton mass matrix even when it is assumed to be diagonal at the Plank scale. Recently, Barbieri and Hall found that the slepton mixing thus generated is very large owing to the large top-quark Yukawa coupling [34]. Then, $\mu^+ \to e^+\gamma$ occurs due to this slepton mixing through loop diagrams. The predicted branching ratio is within the reach of near-future experiments.

The branching ratio of $\mu^+ \to e^+\gamma$ predicted in SUSY SU(5) models [35] is shown in Figure 12. It ranges from 10^{-15} to 10^{-13} for a right-handed slepton mass of 100 to 300 GeV/c^2. The effect of higher dimensional operators in SU(5) SUSY-GUT was considered, and the branching ratio was found to be enhanced for large $\tan\beta$ [36].SO(10) SUSY GUT models give even larger values, 10^{-13} to 10^{-11}, via an enhancement of $(m_\tau/m_\mu)^2 \sim 100$ [34]. This is because of the existence of loop diagrams whose magnitude is proportional to the τ-lepton mass in such models.

Furthermore, the recent experimental hints of non-vanishing neutrino masses and mixing suggested by the atmospheric neutrino anomaly inspire additional LFV



(a) (b)

Figure 12: *Predictions of $\mu^+ \to e^+\gamma$ branching ratio in SU(5) SUSY models.*

contributions in SU(5) SUSY-GUT models [37]. One such model includes a heavy right-handed Majorana neutrino of 10^{14}–10^{15} GeV with a ν_μ-ν_τ mixing of $\sin^2(2\theta_{\nu_\mu\nu_\tau}) \sim 1$ (as suggested by Super Kamiokande). This contribution also enhances LFV by a factor of about $(m_\tau/m_\mu)^2$ over the minimal SU(5) SUSY-GUT models.

Models with gauge-mediated SUSY breaking in general do not lead to LFV since the messenger-matter interaction is flavor-blind. However, recently there have been discussions of mechanisms to generate significant LFV, such as messenger-matter mixing. In such models, a large branching ratio for $\mu^+ \to e^+\gamma$ is possible [38]. SUSY models with R-parity breaking also tend to predict a large $\mu^+ \to e^+\gamma$ branching ratio, which is sensitive to those couplings of R-parity breaking (λ and λ') that are not constrained strongly by the limits on proton decay [39].

In SUSY-GUT models, the $\mu^- - e^-$ conversion process in nuclei, for instance in Ti, has about 1/250 the branching ratio of $\mu^+ \to e^+\gamma$. Therefore, a search for $\mu^+ \to e^+\gamma$ at the level of 10^{-14} is comparable to that for $\mu^- - e^-$ conversion in nuclei at the level of 10^{-16}. The nuclear dependence of the latter has also been calculated taking account of relativistic atomic effects, Coulomb distortion, finite nuclear size and nucleon distribution [40]. It was found that the ratio of $\mu - e$ conversion to $\mu^+ \to e^+\gamma$ varies from 389 for ^{27}Al to 238 for ^{48}Ti, and increases again to 342 for ^{208}Pb. On the other hand, extra logarithmic enhancement of $\mu^- - e^-$ conversion (and also $\mu^+ \to e^+e^-e^+$) over $\mu^+ \to e^+\gamma$ in loop diagrams involving light charged fermions is possible [41]. It could occur for SUSY models with R-parity breaking, but not for R-parity conserving SUSY models or in SUSY-GUT models.

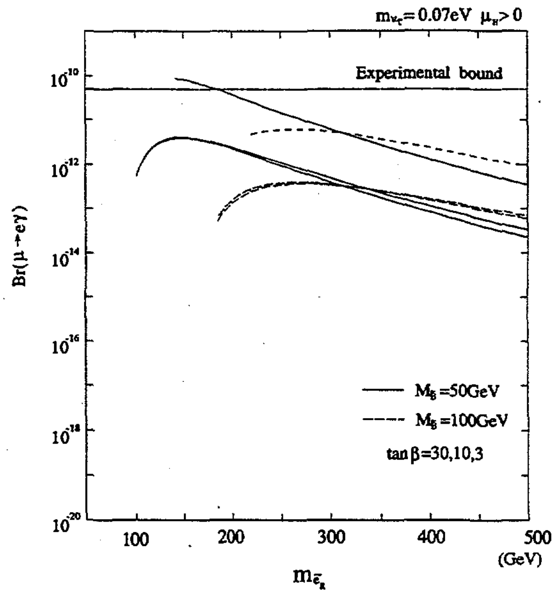


Figure 13: *Predictions of $\mu^+ \to e^+\gamma$ branching ratio in SU(5) SUSY models with right-handed Majorana neutrino as a function of $m_{\tilde{e}_R}$ when the Yukawa coupling constant of ν_τ is as large as that of top quark.*

3.1 $\mu^+ \to e^+\gamma$

The event signature of $\mu^+ \to e^+\gamma$ is a coincident positron and photon, moving collinearly apart, each with energy equal to half the muon mass ($m_\mu/2 = 52.8$ MeV). Two major backgrounds to a search for $\mu^+ \to e^+\gamma$ are (1)radiative muon decay, $\mu^+ \to e^+\nu\bar{\nu}\gamma$, where e^+ and photon are emitted back-to-back and the ν_e and $\bar{\nu}_\mu$ carry off little energy and (2) an accidental coincidence of an e^+ from $\mu^+ \to e^+\nu\bar{\nu}$, accompanied by a high energy photon. The latter might either be from $\mu^+ \to e^+\nu\bar{\nu}\gamma$ decay, or from external bremsstrahlung or annihilation-in-flight of e^+s from $\mu^+ \to e^+\nu\bar{\nu}$. Detector resolutions must be excellent to eliminate these backgrounds.

A recent search was done by the MEGA collaboration at Los Alamos National Laboratory (LANL). The MEGA detector consisted of eight cylindrical chambers for positron tracking and concentric pair spectrometers for photon detection, all placed inside a superconducting solenoid magnet. MEGA completed its data-taking in 1995. A preliminary new 90% c.l. limit of 4.2×10^{-11} based on analyzing 16 % of the data was reported in this workshop [42]. An extrapolation to the complete MEGA data set yields $(3-6) \times 10^{-12}$.

A new experiment on $\mu^+ \to e^+\gamma$ with a sensitivity of 10^{-14} is being considered at PSI where a surface muon beam of a few $\times 10^8$/sec is available [43]. In the Letter of Intent, the options considered for a positron detector are a solenoidal-field spectrometer with a limited solid angle or a ring-image focusing spectrometer. The options for photon detection are liquid-Xe or high-speed luminous inorganic crystals such as Ce-doped ortho-silicates or ortho-aluminates of Yttrium, Lutetium and/or

Ytterbium.

For a future JHF experiment, the use of polarized muons for a search for $\mu^+ \to e^+\gamma$ has been proposed for further improvement in the background rejection [44].

3.2 $\mu^- - e^-$ Coherent Conversion in Nuclei

The signature of $\mu^- - e^-$ coherent conversion in nuclei is a mono-energetic single electron of $(m_\mu - B_\mu)$ MeV emitted from μ^- capture (m_μ and B_μ are the muon mass and the binding energy of the 1s muonic atom respectively). Major backgrounds are muon decay in orbit from a muonic atom (in which the e^- endpoint energy is the same as the energy of the signal), radiative pion and muon capture and cosmic rays. Accidental backgrounds are not generally a problem, but the beam purity and the efficiency of cosmic-ray vetoing are crucial.

The ongoing experiment is SINDRUM II at PSI. The 1993 run with a Ti target yielded a 90 % C.L. upper limit of $B(\mu^- Ti \to e^- Ti) < 6.1 \times 10^{-13}$, $B(\mu^- Ti \to e^+ Ca(g.s.)) < 1.7 \times 10^{-12}$, and $B(\mu^- Ti \to e^+ Ca(e.s.)) < 3.6 \times 10^{-11}$ where $g.s$ and $e.s.$ are ground state and excited state transitions, respectively. For Pb, it yielded $B(\mu^- Pb \to e^- Pb) < 4.6 \times 10^{-11}$. For the next stage of the experiment, the "pion-muon converter" (PMC) which consists of a straight superconducting solenoid magnet of 8.5 m in length, designed to reduce beam pion contamination, is being prepared. With this PMC, a sensitivity of 2×10^{-14} is thought to be achievable [45].

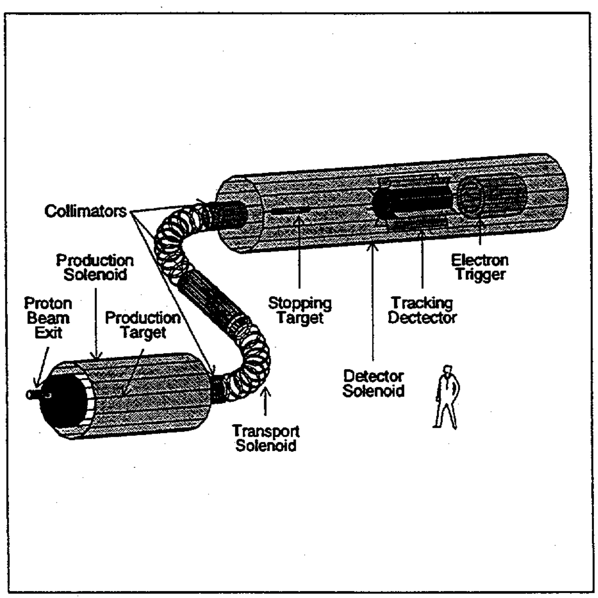


Figure 14: *Schematic layout of the MECO detector.*

There is a new initiative at the BNL AGS called the MECO (Muon Electron COnversion) experiment (E940) which is a search for $\mu^- Al \to e^- Al$ with a proposed sensitivity of better than 10^{-16} [46]. The setup consists of a graded high-field superconducting solenoid for muon capture ($\sim 1.2\,\mathrm{m}$ bore and $4\,\mathrm{m}$ length), a curved transport solenoid system which selects momentum and sign of charged particles [47], and a detector with good energy resolution ($\sigma_{RMS} < 300$ keV) that is designed to observe only the 105-MeV signal electrons in a second axially graded solenoidal field. A proton beam pulsed at about 1 MHz with pulse length 50 nsec is used to minimize beam-associated backgrounds, in particular from pions. A rate of $\sim 10^{11}$ μ^- per cycle stopping in a thin Al target is expected. A schematic layout of the MECO detector is shown in Fig.14.

4 Rare Pion Decay

The subject of rare decays of charged pions is somewhat quiescent at the moment. One exception is an attempt to make a precision measurement of the branching ratio of pion beta decay: $\pi^\pm \to \pi^0 e^\pm \nu$. This is an example of a process that is rendered rare (BR $\sim 10^{-8}$) solely by virtue of its small phase space. This measurement is an almost theory-free method of determining V_{ud}. The PIBETA experiment [48] at PSI aims at a 0.5% measurement of the rate of $\pi^\pm \to \pi^0 e^\pm \nu$.

There is a bit more activity in neutral pion work, mainly as a by-product of studies of kaon decays. This comes about because kaon decays can be a very good source of tagged π^0's. Thus the KTeV experiment uses $K_L \to 3\pi$ decays to study $\pi^0 \to e^+e^-$ [49] and $\pi^0 \to e^+e^-e^+e^-$, AGS-865 uses $K^+ \to \pi^+\pi^0$ decays for the same purpose [50]. In the same way, AGS-787 has used $K^+ \to \pi^+\pi^0$ decays to put limits on $\pi^0 \to \nu\bar{\nu}$ [51] and on $\pi^0 \to \gamma X^0$ [52]. This kind of work is expected to continue as K decay experiments are pursued.

5 Conclusion

Studies of rare kaon decays are entering an interesting new phase wherein they can deliver important short-distance information. It should be possible to construct an alternative unitarity triangle to that determined in the B sector, and thus perform a critical check of the Standard Model by comparing the two. Rare muon decays are beginning to constrain supersymmetric models in a significant way, and future experiments should reach sensitivities which this kind of model must show effects, or become far less appealing.

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