TWO RARE KAON DECAYS: A PRIMER

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I. Summary

Searches for the decays $K_L^0 \to \mu e$ and $K^+ \to \pi^+ \mu e$, forbidden by separate lepton number conservation, are sensitive to the existence of particles whose masses are far above those directly accessible with present accelerators or machines likely to be built in the foreseeable future. Branching fractions of $\sim 10^{-11}$, two orders of magnitude below present upper limits, can be measured with existing machines and current techniques. Measurements of smaller branching fractions will necessitate more intense kaon beams.

II. Introduction

In this report we consider the experimental study of two rare kaon decays, $K_L^0 \to \mu e$ and $K^+ \to \pi^+ \mu e$, with a view toward answering the following questions:

1. Are these decays interesting from the physics point of view?

2. Can significantly improved upper limits on these decay rates be achieved at present machines with present techniques or are new machines or techniques a prerequisite?

The first question is answered easily and briefly in Section III; the rest of the report is concerned with the second question.

III. Theory

The observation of the decay $K_L^0 \to \mu e$ or $K^+ \to \pi^+ \mu e$ would constitute prima facie evidence for the violation of muon and electron number conservation. As such, improved limits on these decays (and others, like $\mu \to e\gamma$) are inherently interesting. Is there any reason to suspect that these decays might occur? In recent years theories have arisen to remedy certain perceived defects of the "standard" Weinberg-Salam-Glashow model of the electroweak interaction. In particular, a dynamical mechanism has been sought to bring about spontaneous symmetry breaking, thereby removing the somewhat ad hoc Higgs scalar fields from the theory. Several current models incorporating dynamical symmetry breaking for the weak interaction indicate that flavor changing neutral currents (technipions) or other massive particles may mediate such rare processes as $K_L^0 \to \mu e$, $K^+ \to \pi^+ \mu e$, $\mu \to e\gamma$, etc.[1] Branching fractions are expected[1] to be not far below present upper limits, which are $<1.57\times10^{-9}$ for $K_L^0 \to \mu e$,[2] and $<4.8\times10^{-9}$ for $K^+ \to \pi^+\mu^+e^-$.[3]

IV. Feasibility of Experiment

A. General Remarks

In order to improve significantly upon the present upper limits of order 10^{-9} for the two decay modes in question, one would design an experiment to achieve a sensitivity of $<10^{-11}$. Clearly, such a measurement requires a high flux of kaons and a background rate below the level of the branching fraction to be measured. We note parenthetically that the present upper limits come from experiments that were not designed to search for these rare decays. The $K_L^0 \to \mu e$ limit was a by-product of an experiment that set an upper limit of 3.1×10^{-9} on the branching fraction for $K_L^0 \to \mu^+\mu^-$.[2] Subsequently, the two muon decay was extablished to occur at $(9.1\pm1.9)\times10^{-9}$.[4] If we disregard the $K_L^0 \to \mu e$ limit from Clark et al.,[2] then the best upper limit is 6.3×10^{-6}.[5] The $K^+ \to \pi^+\mu^+e^-$ limit was obtained in an experiment to study K^+_{e4} decays.[3]

In Section B we assume that all backgrounds can be eliminated and compare kaon fluxes at existing and proposed accelerators. In Section C we consider details of experimental technique, paying particular attention to background processes.

B. Comparison of Accelerators

As of this writing, one proposal has been submitted to measure $K_L^0 \to \mu e$,[6] and one to measure $K^+ \to \pi^+\mu^+e^-$.[7] The former is an experiment at KEK in Japan. The latter is an approved experiment (#777) at the Brookhaven AGS. A letter of intent to submit a proposal to search for $K_L^0 \to \mu e$ at 10^{-11} has been received at Brookhaven.[8]

In Table I we compare existing K_L^0 beams at KEK, Fermilab, and Brookhaven. In the KEK column, the figures are drawn from the proposal mentioned above. In the latter two cases, for the sake of specificity, we have chosen 10^{-12} as the design goal of a hypothetical $K_L^0 \to \mu e$ experiment. An overall acceptance (geometrical solid angle and detection efficiency combined) of 10% has been assumed for the decay $K_L^0 \to \mu e$.[9] The Fermilab figures correspond closely to recent measurements in the Meson Lab M3 beam line,[10] where the K_L^0 flux is $\sim 2.4\times10^7$ $K_L^0/10^{12}$ protons/μsr at a production angle of 0°. Therefore a neutral beam of cross-sectional area 25 cm × 7 cm at the end of the decay volume (460 m from the target) contains $\sim 10^7$ K_L^0's for 5×10^{12} protons on target. At Brookhaven the corresponding figure is $\sim 2.4\times10^5$ $K_L^0/10^{12}$ protons/μsr.[11] (The differential production cross section is roughly proportional to incident particle momentum, $d^2\sigma/d\Omega dp \propto p$, so $d\sigma/d\Omega \propto p^2/2$, which suggests that the flux at Fermilab should indeed be about two orders of magnitude larger than at the AGS.) Thus at Brookhaven a beam of comparable area (200 cm^2) 22 meters from the production target contains $\sim 10^7$ K_L^0's for 10^{12} protons on target. These numbers are only approximate: K_L^0 fluxes depend upon target dimensions and composition, as well as production angle. As the production angle increases the K_L^0 flux drops, but the neutron flux drops even faster, which might be desirable if the experiment is limited by neutron-induced backgrounds. If one could withstand higher rates in the detector, at both Fermilab and Brookhaven one might request 10^{13} protons/pulse on target. The parameters in the table are intended, however, to be realistic.

The crucial numbers to be gleaned from Table I are the following:

1. the number of K_L^0 decay candidates needed to set an upper limit of 10^{-12} at the 90% confidence level (2.3×10^{12}),

2. the number of K_L^0's which decay per second in the decay volume (K_L^0 decays/pulse × pulses/second), and

3. the detector acceptance.

Table I. Comparison of Accelerators for $K_L^0 \to \mu e$ Experiment.

	KEK	Fermilab	BNL
Sensitivity	5×10^{-11}	10^{-12}	10^{-12}
p Energy (GeV)	12	400	28
Repetition rate	1/2 sec	1/15 sec	1/2.5 sec
p/pulse on target	10^{12}	5×10^{12}	2×10^{12}
Beam solid angle (μsr)	50	0.083	41.3
K_L^0/pulse		10^7	2×10^7
$\langle p\rangle_{K_L^0}$ (GeV/c)	∿3	∿75	∿5
Distance from target to decay region (m)	14.7	210	7
Length of decay region (m)	10	250	15
K_L^0 decays/pulse in decay region	$3\text{-}5\times10^5$	10^6	1.8×10^6
Detector acceptance	5%	10%	10%
No. $K_L^0 \to \mu e$ decay candidates needed	5×10^{10}	2.3×10^{12}	2.3×10^{12}
No. pulses needed	$3.3\text{-}2\times10^6$	2.3×10^7	1.3×10^7
No. hours needed	1,600	$10^5 \simeq 11$ yr	9,100

For identical numbers of K_L^0's decaying per pulse in the decay volume, and identical detector acceptances, the preferred machine is obviously the one with the highest repetition rate (pulses/second). At high energies, one must lengthen the decay region as much as possible to see as many K_L^0 decays as possible, but more importantly, at least at Fermilab, one is limited by the cycle time of the accelerator. The alternative at Fermilab, higher numbers of K_L^0's per pulse ($>10^7$) with more protons on target, carries with it higher single particle fluxes through the detector, perhaps straining its rate capabilities, and increasing background rates from interactions of neutrons in the beam. At Brookhaven, if one could increase the detector acceptance, or lengthen the decay volume, or increase the K_L^0 flux, one would still have difficulty attaining a sensitivity of 10^{-12} in a reasonable time. Simply based on these event rate considerations, an experiment to measure $K_L^0 \to \mu e$ to 10^{-11} appears to be within reach at the AGS.

The possibility of building a new accelerator at Los Alamos, LAMPF II, is presently being studied.[12] LAMPF II might accelerate protons to 16 GeV/c at a repetition rate of 60 Hz, with 10^{13} protons/pulse. The extracted beam would be "stretched", thereby yielding 6×10^{14} protons/second with a duty factor of 100%, making possible very intense kaon beams. With a modest 10^8 K_L^0's produced per second, about 10^7 K_L^0's would decay per second in a 10-m-long decay volume ($\langle p\rangle_{K_L^0} \sim 3$ GeV/c). If the detector acceptance were 10%, the experiment could be performed in 640 hours. (To translate such a figure into "real" time, one must also fold in the experiment's "deadtime" per second.) One could take advantage of such high K_L^0 intensities by defining a beam of small solid angle at a large angle relative to the incident proton beam. As we shall see, a "pencil thin" beam would help in distinguishing three-body decay backgrounds from two-body decays.

Serious discussion about building a kaon and neutrino "factory" at TRIUMF has centered around a primary proton beam energy in the 8-15 GeV range.[13]

With suitable modifications, these remarks apply to charged kaon beams as well. That is, the three numbers crucial to the K_L^0 experiment are also crucial to the K^+ experiment. However, the characteristics of a charged kaon beam differ considerably from those of a neutral kaon beam. With a charged beam, one can select a beam momentum and a momentum bite. This provides an additional kinematic constraint in the selection of a final sample of events. A charged kaon beam can be steered to any desired angle with respect to the incident proton beam to avoid target-associated backgrounds. Furthermore, it may be confined to a small cross-sectional area, unlike the neutral beam whose cross-section grows quadratically with distance from the target. In addition, quite satisfactory K^+ yields can be had at existing accelerators. For example, at the AGS one expects 2×10^7 K^+'s/pulse at 4 GeV/c (with a momentum spread of ∿10%) for only 2.4×10^{11} protons/pulse,[7] far below the available AGS proton intensity.

C. Detector Design and Background Rejection

In this section we assume that high fluxes of kaons are at hand or within reach, and as such do not constitute the limitation on our ability to measure extremely small branching fractions. Indeed, these measurements are difficult because the detector must not only be sensitive to the decay of interest, it must be capable of beating down competing background processes to a fantastically low level. For this reason, the detector design is discussed in conjunction with background rejection.

We shall discuss the decays $K_L^0 \to \mu e$ and $K^+ \to \pi^+\mu e$ separately. However, one simple observation applicable in both cases is that the trigger rate from a multitude of other decays must be suppressed by a large factor in order to keep the number of events written to tape at a manageable level. An upper limit (for design purposes) might be 10^7 events, which would require a trigger rejection factor of 2.3×10^6 for a branching fraction measurement at the 10^{-12} level (2.3×10^{13} kaon decays in the decay volume × 10% acceptance for the decay mode to be measured = 2.3×10^{12} kaon decay candidates). For 10^6 kaon decays per pulse, this yields one event every 2.3 pulses. Of course one must admit a small fraction of certain kaon decays for normalization and calibration purposes. Even a scant 10 calibration/normalization triggers per pulse would result in a data sample of 2.4×10^8 events, including triggers from backgrounds, so some restraint must be exercised in this regard. The point is that the background rejection in the trigger must be extremely effective. In the discussion that follows we shall work around a trigger rejection factor of 2.3×10^6 for background processes, which means an additional rejection factor of at least 10^7 must be provided in the analysis of the data.

Before considering specific decays, let us be more explicit about the meaning of a trigger rejection factor of 2.3×10^6. For example, let us assume that all of the backgrounds to $K_L^0 \to \mu e$ come from other K_L^0 decays. The equation which fixes the maximum tolerable trigger efficiency for each decay mode is the following:

$$2.3\times10^{13}\ K_L^0 \text{ decays} \times \{0.388\times\text{eff}(K_L^0 \to \pi e\nu) + 0.270\times\text{eff}(K_L^0 \to \pi\mu\nu) + 0.124\times\text{eff}(K_L^0 \to \pi^+\pi^-\pi^0) + \ldots\} = 10^7\ K_L^0 \text{ decays written to tape.}$$

The trigger efficiency for each decay mode is multiplied by its branching fraction. If the trigger efficiency is contrived to be zero for all decay modes except $K_L^0 \to \pi e\nu$ (and $K_L^0 \to \mu e$), for instance, then the maximum tolerable efficiency for $K_L^0 \to \pi e\nu$ is 1.12×10^{-6}. To achieve such a small trigger efficiency one depends upon the geometric acceptance of the detector aperture, extremely small particle misidentification probabilities, and trigger logic which is biased against the decay.

With these general remarks concerning the trigger in mind, let us now consider the decay modes from the data analysis point of view. If we are satisfied that the backgrounds can be rendered negligible, at least in principle, then we may return to the subject of the trigger.

i. $\underline{K_L^0 \to \mu e}$.

The signature of the decay $K_L^0 \to \mu e$ is a pair of oppositely charged particles whose invariant mass is equal to the K_L^0 mass. Particle identification methods must indicate that one is an electron and the other a muon. One can insist that the reconstructed muon and electron trajectories form a good vertex, the K_L^0 decay point, within the beam and decay volume. Then, given the position of the production target, one can demand that the kaon, electron, and muon trajectories be coplanar and that transverse momentum be conserved. Alternatively, assuming that the kaon decay was two-body, one can calculate the K_L^0 momentum vector and reject the event if the reconstructed K_L^0 trajectory does not come close to the target.[14] Thus background rejection relies heavily upon kinematic constraints and particle identification. The principal sources of background are likely to be the following:

a. $K_L^0 \to \pi e\nu_e$. We distinguish two cases, one in which the pion decays to a muon, $\pi \to \mu\nu_\mu$, the other in which the pion is misidentified as a muon. In both cases, the troublesome region of phase space is near the point at which the neutrino energy is zero ($E_{\nu_e} = 0$) in the K_L^0 rest frame. Fortunately, the Dalitz-plot density for K_{e3} and $K_{\mu3}$ decays vanishes as $E_\nu \to 0$, whether the coupling is vector, scalar, or tensor.[15]

In the first case, $K_L^0 \to \pi e\nu_e$ followed by $\pi \to \mu\nu_\mu$, the event most likely to mimic a true $K_L^0 \to \mu e$ decay is one in which the electron-neutrino energy vanishes, and the daughter muon trajectory is collinear with the parent pion trajectory. Then the μ-e invariant mass is 489.24 MeV/c^2, only 8.43 MeV/c^2 below the K_L^0 mass (497.67 MeV/c^2). If the invariant mass resolution is σ = 2.1 MeV/c^2, and we make cuts $\pm2\sigma$ around the K_L^0 mass, then the odds against this event satisfying the cut are only 21:1. To determine if this resolution is good enough, we must know how many of the 10^7 events to be analyzed populate the steeply falling μ-e invariant mass spectrum near the kinematic maximum. To be more precise, we compute the number of background events expected above the lower K_L^0 mass cut as follows: we divide the number of events that would, for an ideal detector, fall at a given mass which is $N\sigma$ below the K_L^0 mass cut by twice the odds against such an event deviating by $N\sigma$; we then integrate over mass. Since the odds grow exceedingly fast with N, the number of standard deviations away from the cut, the only mass relevant to choosing a desirable resolution is the one at the kinematic maximum. Notice that if the mass resolution is significantly better than 2.1 MeV/c^2, for example σ = 1.2 MeV/c^2, then the odds against an event at the kinematic maximum falling within the $\pm2\sigma$ cuts are already so high, 1.7×10^6:1, that we need not worry about how many events survive all the event selection requirements, save the final cut on invariant mass. The experiment of Clark et al. obtained an invariant mass resolution (σ) better than 1.0 MeV/c^2.[2] Clearly, excellent mass resolution is a necessity, though one need not do better than σ = 1.0 MeV/c^2. This conclusion depends, however, upon the assumption that the experimental mass resolution may be described by a Gaussian distribution. Excellent mass resolution requires excellent position and momentum resolution, which necessitate a low-mass detector to minimize multiple scattering. Even though the 1/e multiple scattering angle Θ_0 is inversely proportional to momentum, a higher energy accelerator would not necessarily be favored in this respect, since the longitudinal dimensions of the apparatus must scale with p if the momentum resolution is to be preserved using an analyzing magnet with a fixed transverse-momentum kick.[16]

If the muon trajectory is not collinear with the pion trajectory, and the K_L^0 decay vertex requirement can still be satisfied, then the measured invariant mass will be even lower, provided the muon momentum is measured correctly. A good K_L^0 vertex would be formed if the pion decayed instantly or if it decayed downstream of the tracking devices. Most of the events in the first category would be rejected by the requirement that the reconstructed K_L^0 trajectory intersect the target. Events in the second category would be hard to throw out except by the invariant mass cut. If the pion decayed upstream of the apparatus, but downstream of the K_L^0 decay point, only if the muon trajectory lay in the plane containing the kaon and electron trajectories could a good K_L^0 decay vertex be formed. If one could afford to sacrifice kaon flux by shrinking the solid angle of the neutral beam, then the probability that such an event would form a vertex outside the beam, and thereby be rejected, would increase. Nevertheless, most of the events in this third category would fail the target-intercept cut. With more frequent sampling of charged particle positions in the apparatus, at the cost of increased multiple scattering, a kink in a track from a pion decay that occurred within the apparatus might be discernible. Bear in mind, though, that the Q-value of the decay $\pi \to \mu\nu$ is only about 34 MeV, and that no detector can make a perfect spatial reconstruction of particle trajectories. The proviso above that the muon momentum be measured correctly is an important one, since an additional 30 MeV/c transverse momentum imparted to the muon in the direction opposite the magnet's p_t kick can boost the μ-e effective mass up to the K_L^0 mass, if the pion decays between chambers straddling the analyzing magnet.

In the second case, in which the pion is misidentified as a muon, the invariant mass of the π-e pair is calculated giving the pion the muon mass. When the neutrino energy is zero, this results in an invariant mass of 481.71 MeV/c^2, 15.96 MeV/c^2 below the K_L^0 mass.

We see that if the detector's invariant mass resolution is better than about 1.2 MeV/c^2 and the muon momentum is measured correctly, then $K_L^0 \rightarrow \pi e \nu$ decays will not contaminate a $K_L^0 \rightarrow \mu e$ signal. Achieving such a resolution might not be as difficult as ensuring that a small number of events survive the trigger. To be specific, let us assume that 10% of the pions decay upstream of the muon identification apparatus. Let us also assume that the probability of misidentifying a pion as a muon is 1%, using a conventional segmented Fe-scintillator muon filter. Then the maximum tolerable detection efficiency for $K_L^0 \rightarrow \pi e \nu$, for the case in which the pion is misidentified, is 1.25×10^{-4}. If the geometrical acceptance of the detector aperture is 5% for this decay, then the remaining trigger logic must furnish a rejection factor of 400. The other case, in which the pion decays, makes more severe demands of the trigger. For the same geometrical acceptance, the trigger logic must provide a rejection factor of at least 4.5×10^3. This means that the trigger must take full advantage of a "hardware" coplanarity requirement, and perhaps a vertex requirement, to the extent that multiple scattering and the cross-sectional area of the neutral beam allow. Clearly, one must carry out a detailed Monte Carlo simulation of the experiment to see if this is feasible. The consequence of falling short of the goal is swallowing many more events per pulse. (The fraction of pions which decay before the muon identification apparatus is essentially independent of beam energy, since the lengthened decay volume compensates for the longer lifetime of the pion at a higher energy machine. However, the probability of misidentifying a pion as a muon decreases with increasing energy.)

b. $K_L^0 \rightarrow \pi\mu\nu_\mu$. This decay is a less worrisome source of background events than its counterpart $K_L^0 \rightarrow \pi e \nu$. If the pion decays to an electron, $\pi \rightarrow e\nu$, the maximum μ-e invariant mass is 21.02 MeV/c^2 below the K_L^0 mass. If the pion is misidentified as an electron, the kinematic maximum is 41.16 MeV/c^2 below the K_L^0 mass. More importantly, the $\pi \rightarrow e\nu$ branching fraction is $\sim10^{-4}$, and the probability that a pion is misidentified as an electron can be made extremely small, of order 10^{-7} or better.[7] These decays do not pose a problem for either the trigger or the final data analysis. Other possibilities, for instance $K_L^0 \rightarrow \pi\mu\nu$ followed by $\pi \rightarrow \mu\nu$ and $\mu \rightarrow e\nu\nu$, or $K_L^0 \rightarrow \pi\mu\nu$ followed by $\mu \rightarrow e\nu\nu$ and misidentification of the pion, are greatly suppressed by the long lifetime of the muon, the small probability of misidentifying a pion as a muon, the extremely small probability of misidentifying a muon as an electron ($<10^{-7}$),[7] or some product of these. In any case, the invariant mass of the pair of charged particles will be well below the K_L^0 mass.

c. Other K_L^0 decays. One can comb the list of observed K_L^0 decays for potential backgrounds, for example $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ followed by $\pi \rightarrow \mu\nu$ and $\pi \rightarrow e\nu$, yet in no case can the measured invariant mass come as close to the K_L^0 mass as in the $K_L^0 \rightarrow \pi e \nu$, $\pi \rightarrow \mu\nu$ decay sequence. All of the two-body decays have branching fractions of 2×10^{-3} or less. The decays $K_L^0 \rightarrow \pi^+\pi^-$ and $K_L^0 \rightarrow \mu^+\mu^-$ are interesting in their own right, and so would be included in the trigger if only for calibration and normalization. (If the detector acceptance were 10% for these two decays, and 10^6 K_L^0's decayed per pulse, they would yield 200 events per pulse and one event every 10^3 pulses, respectively.) At the same time one might search for $K_L^0 \rightarrow e^+e^-$.

A conceivable background to the decay $K_L^0 \rightarrow \mu e$ is the allowed decay $K_L^0 \rightarrow \mu e \nu_\mu \nu_e$, though the branching fraction is probably of order 10^{-11}. This should be calculated! Of course only the small region of phase space near $E_{\nu_e} = E_{\nu_\mu} = 0$ would contribute to the background.

d. Other backgrounds. Background rates from interactions of beam neutrons with the residual gas in the decay volume or with the decay pipe walls are difficult to estimate accurately. One's best defense is a very good vacuum inside the beam pipe (<2 μm Hg). In addition, good shielding of the apparatus from target-associated muons can help.

We conclude this discourse on the decay $K_L^0 \rightarrow \mu e$ with some observations about detector design and $K_L^0 \rightarrow \mu^+\mu^-$ experiments. The $K_L^0 \rightarrow \mu e$ apparatus must have the following characteristics:

1. a large acceptance,
2. excellent mass resolution,
3. an effective two-body trigger, and
4. excellent particle identification.

These requirements suggest a magnetic spectrometer consisting of drift or multiwire-proportional chambers (MWPC's), scintillation counters for triggering and fast timing, and perhaps Cherenkov counters, Pb-glass, and a steel wall for particle identification. While minimizing multiple scattering, atmospheric-pressure Cherenkov counters afford the best pion-electron and muon-electron separations, for particle momenta less than ~10 GeV/c. At higher momenta, delta-ray production becomes an important concern. One can envision at least two different magnetic field configurations. The KEK proposal, for example, calls for a toroidal magnetic field, which has two virtues: the acceptance in the azimuthal angle φ is nearly complete, and the decay secondaries remain in the same plane downstream of the magnet, for K_L^0 decays which occur on the axis of symmetry. Thus triggering and particle identification may be done downstream of the spectrometer, so as not to compromise mass resolution. While a dipole magnet is not so obviously matched to the topology of the $K_L^0 \rightarrow \mu e$ decay, a clean two-body trigger can be made by setting the p_t kick of the magnet at 238 MeV/c, and selecting events with two parallel tracks downstream of the magnet. This technique preferentially selects events for which the muon and electron have the maximum allowed momentum transverse to the beam direction, and for which the muon and electron travel in a plane normal to the direction of the magnetic field. While it further restricts the data sample to events with a particular sign of charge on one side of the apparatus, neither particle diverges from the beam axis downstream of the magnet, which is not the case for the toroidal field design. One can conceive of other two-body triggers using a dipole magnet which are not so costly in terms of acceptance.

Since the requirements of an experiment to detect

$K_L^0 \to \mu\mu$ are manifestly similar to those of the $K_L^0 \to \mu e$ experiment, it behooves us to determine why the $K_L^0 \to \mu\mu$ experiments observed so few events. The experiments of Carithers et al.[4] detected nine $K_L^0 \to \mu\mu$ decays using an MWPC spectrometer at the end of a 6 m decay region. The neutral beam had a small solid angle, 18 μsr, and was brought out at 4.7° from an internal target, resulting in a modest intensity of $\sim 10^6$ $K_L^0/10^{12}$ protons.[17] The experiment of Fukushima et al.,[4] originally intended to measure $K_S^0 \to \mu\mu$, had a decay volume only 3.05 m long. Though the beam solid angle was large, 250 μsr, the experiment was run at a low intensity, $\sim 10^{11}$ protons/pulse, yielding a paltry $\sim 10^4$ K_L^0 decays/pulse in the decay volume. Three $K_L^0 \to \mu\mu$ events were observed. Finally, the experiment of Shochet et al.[4] obtained a signal of 16 events with a background of 0.6 events. Whereas the two previous experiments were performed at the AGS, this one was conducted at the Argonne ZGS, with a proton beam of 12 GeV/c momentum producing a neutral beam at 4° in a large solid angle of 700 μsr. Approximately 10^6 K_L^0's with momenta between 2 and 7 GeV/c decayed in a 10.4-m-long evacuated volume for 2.5×10^{11} protons on target. The experimenters triggered a dual-arm spark-chamber magnetic spectrometer on two parallel muons downstream of the analyzing magnets. It is not clear from the published results why this experiment, apparently not limited by kaon intensity, gathered so few events. Perhaps the overall acceptance, including particle detection efficiencies, was low.

The principal background in these $K_L^0 \to \mu\mu$ experiments came from the analog of the principal background expected in a $K_L^0 \to \mu e$ experiment, namely, $K_L^0 \to \pi\mu\nu$ decays in which the pion decayed to a muon within the spectrometer in such a way as to introduce an error in the measurement of the momentum. If the daughter muon momentum were measured correctly, the maximum μ-μ invariant mass would be 488.8 MeV/c^2. In each of these experiments, a requirement that both tracks have a smooth trajectory was imposed to suppress this background. The experiment of Shochet et al. found that the tail in the invariant mass plot could be fit by an exponential of the form $16.9\times\exp-\{(M - 483)/2.2\}$ with M in MeV/c^2. Their mass resolution for $K_L^0 \to \pi^+\pi^-$ was $\sigma = 2.1$ MeV/c^2. Had the $K_L^0 \to \mu\mu$ branching fraction been four orders of magnitude smaller ($\sim 10^{-12}$), they would have had $\sim$389 background events above 492 MeV/c^2 for each $K_L^0 \to \mu\mu$ decay. However, for a mass resolution of 1.1 MeV/c^2, about 0.1 background events above 495.5 MeV/c^2 would have accompanied each true decay, assuming the exponential form $\exp-\{(M - 483)/1.1\}$. This extrapolation provides another compelling argument for superb mass and position resolution in an experiment to search for $K_L^0 \to \mu e$.

ii. $K^+ \to \pi^+\mu e$.

The two decays $K^+ \to \pi^+\mu^+e^-$ ($K^+_{\pi\mu e^-}$) and $K^+ \to \pi^+\mu^-e^+$ ($K^+_{\pi\mu e^+}$) present distinctly different experimental problems. One does not expect to see an electron of charge opposite that of the kaon until the decay chain $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$ occurs, at a level of 2.4×10^{-3}. (The product of the branching fractions for the decay sequence $K^+ \to \pi^+\pi^+\pi^-$, $\pi^- \to \mu^-\nu$, $\mu^- \to e^-\nu\nu$ is 5.5×10^{-2}, yet the long lifetime of the muon mitigates against this as a source of electrons.) On the other hand, $K^+ \to e^+\nu\pi^0$ occurs with a branching fraction of $\sim$5%. The high decay rate to positrons, together with potentially high ambient μ^+ fluxes, favor triggering on the $K^+_{\pi\mu e^-}$ decay mode. However, the branching fractions for the $K^+_{\pi\mu e^-}$ and $K^+_{\pi\mu e^+}$ decays need not be the same.

As far as backgrounds are concerned, the most probable means of obtaining the particles π^+, μ^+, and e^- in the final state (simply according to products of branching fractions) is through the decay $K^+ \to \pi^+\pi^+\pi^-$ followed by $\pi^+ \to \mu^+\nu$ and $\pi^- \to e^-\nu$. That probability is only 1.4×10^{-5}. Though the decay $K^+ \to \pi^+\pi^+\pi^-$ can also yield π^+, μ^-, and e^+ in the final state, a more likely sequence is $K^+ \to e^+\nu\pi^+\pi^-$ followed by $\pi^- \to \mu^-\nu$, at 3.9×10^{-5}. In either the $K^+_{\pi\mu e^-}$ or the $K^+_{\pi\mu e^+}$ experiment, one should worry more about backgrounds resulting from particle misidentification. Then one finds that the most important backgrounds arise from the decays $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^0$, and $K^+ \to \mu^+\nu\pi^0$ (where $\pi^0 \to e^+e^-\gamma$ occurs instantly). Notice that in the $K^+ \to \pi^+\pi^+\pi^-$ case, one always misidentifies a heavier particle as a lighter one. This tends to lower the measured invariant mass of the three detected charged particles. Furthermore, except in the case in which two pions are misidentified, there are undetected neutrinos carrying off some energy, further suppressing the maximum invariant mass that could be measured. However, for the decays $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu\pi^0$, one must mistake a positron (or an electron) for a more massive particle. One can differentiate the particles sufficiently well with standard techniques to push the backgrounds to the 10^{-12} level, with the aid of a conventional magnetic spectrometer.[7]

V. Conclusion

The study of extremely rare decays of the kaon affords us a glimpse of phenomena associated with energy scales far beyond those attainable with present accelerators. Experiments that search for muon and electron number non-conservation in the decays $K_L^0 \to \mu e$ and $K^+ \to \pi^+\mu e$ can be expected to set upper limits around 10^{-11} in the near future at existing machines. These experiments will require excellent particle identification, position, and mass resolution in order to suppress backgrounds from other kaon decays to the requisite level. Large acceptance and a high flux of kaons are essential to performing the experiments in a reasonable time. In order to measure branching fractions of 10^{-12} or less more intense kaon beams must be built. Without a significant improvement in detector rate capabilities, measurements below 10^{-14} can not be completed in less than one year of data-taking. At this level, background processes may well be the experimental limitation, rather than the availability of sufficiently high kaon fluxes.

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VII. References

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