PROSPECTS IN LEPTON-FLAVOR VIOLATION

Cyrus M. Hoffman
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Summary

The theoretical and experimental situation regarding lepton-flavor conservation is reviewed and upcoming experiments are described. It is concluded that future improvements in experimental sensitivities will require higher flux, higher quality muon and kaon beams.

Conservation laws have played a central role in the development of physics. These laws are of two types: those that are related to space-time displacements and rotations (such as conservation of energy and momentum), and those that are not (such as conservation of electric charge, lepton number, and baryon number). Conservation of electric charge is expected to be exact because it is related to gauge invariance of the electromagnetic field and its associated massless gauge boson, the photon. It can be shown[1] that lepton or baryon number cannot be associated with a massless gauge boson without violating the equivalence principle, which states that gravitational mass and inertial mass are equivalent. This argument motivates the search for violations of these conservation laws independent of any specific theoretical prediction.

In the early 1960s, the discovery of distinct ν_e and ν_μ validated the concept of separately conserved electron number and muon number. The smallness of upper limits for muon-number-violating processes [for example, $\Gamma(\pi^+ \to e^+\gamma)/\Gamma(\mu^+ \to all) < 2.2 \times 10^{-8}$ in 1964] fostered the belief that separate lepton numbers were exactly conserved quantities. The advent of gauge models of electroweak interactions provided a natural way of understanding such small branching ratios even if lepton numbers are not conserved.

In the "standard model," there are no flavor-changing couplings of the fermions to the neutral gauge bosons or to the Higgs boson. Nevertheless, muon-number conservation would not be expected unless the neutrinos were all exactly massless (or, more strictly, degenerate). The present upper limit for the masses of ν_e, ν_μ, and ν_τ would only allow muon-number-violating processes to occur at rates too small to be detected in presently contemplated experiments.[2] Therefore, searches for lepton-flavor-violating processes probe for extensions to the standard three-generation model. Examples of such extensions are the existence of more than one Higgs doublet,[3] left-right symmetric models,[4] additional leptons (neutral, charged, or doubly charged), models with horizontal interactions,[5,6] and extended technicolor models.[6,7] In general, the existing experimental limits place constraints on the parameters of these models.

It is important that experiments search for all the possible processes. The various models tend to disagree as to which process will have the largest rate. Therefore, the most sensitive model-independent search involves all processes. If lepton-flavor violation is found in any process, the strengths of the other processes will help uncover the underlying mechanism responsible.

The upper limits for muon-number-violating processes achieved before the advent of meson factories are shown in Table I. These experiments were limited by the number of muons incident on the apparatus, although in some instances measurable backgrounds were present. Some of these backgrounds were caused by pion interactions or decays and were magnified by the modest apparatus resolutions.

TABLE I
Premeson Factory Upper Limits

Process	Value (90% CL)	Reference
$\Gamma(\mu^+ \to e^+\gamma)/\Gamma(\mu \to all)$	2.2×10^{-8}	S. Parker, H. L. Anderson, C. Rey, Phys. Rev. 133B, 768 (1964).
$\Gamma(\mu^+ \to e^+e^+e^-)/\Gamma(\mu \to all)$	1.9×10^{-9}	Korenchenko et al., Sov. Phys. JETP 43, 1 (1976).
$\Gamma(\mu^+ \to e^+\gamma\gamma)/\Gamma(\mu \to all)$	4.0×10^{-5}	J. M. Poutissou et al., Nucl. Phys. B80, 221 (1974).
$\Gamma(\mu^-Z \to e^-Z)/\Gamma(\mu^-Z \to \nu_\mu x)$	1.0×10^{-9}	D. Bryman et al., Phys. Rev. Lett. 28, 1469 (1972).

At meson factories (LAMPF, SIN, and TRIUMF), intense pion-free muon beams were constructed. Coupled with improvements in detector resolutions, more sensitive experiments could be performed using experimental designs similar to those performed earlier. In fact, the upper limit for the $\mu^+ \to e^+\gamma$ branching ratio was lowered to 3.8×10^{-9} (Ref. 8) and then to 1.1×10^{-9} (Ref. 9), with detectors nearly identical to that used by Frankel et al.[10] in 1963 to set an upper limit of 4.3×10^{-8}. The lesson to be learned here is that developing higher intensity, clean beams inevitably leads to more sensitive experiments.

Two additional developments led to a $\mu \to e\gamma$ experiment with yet another order-of-magnitude sensitivity. The first was the perfection of a "surface" μ^+ beam.[11] In such a beam, 30-MeV/c μ^+'s result from π^+ decays at rest near the surface of the production target. This beam is clean, intense, and has a range of ≈ 75 mg/cm^2, permitting a very thin stopping target that minimizes multiple scattering and energy loss of the decay products before they are detected. The second development was the use of new experimental technology (segmented NaI detectors, multiwire proportional chambers), which improved the experimental resolutions and reduced the background level still further. The result was an improvement of the upper limit for the $\mu^+ \to e^+\gamma$ branching ratio to 1.7×10^{-10} (Ref. 12). This demonstrates that inventiveness and technological developments will also lead to more sensitive experiments if the particle intensities are high enough to make good use of these advances.

The next chapter in the pursuit of higher resolution $\mu^+ \to e\gamma$ experiments is the Crystal Box experiment[13] (see Fig. 1). This experiment will use 396 NaI (Tℓ) detectors and a cylindrical drift chamber surrounding a stopping target to search for $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, and $\mu^+ \to e^+\gamma\gamma$, each at the $\approx 10^{-11}$ level, at the same time. Some of the parameters of this experiment are given in Table II. The experience gained from the previous $\mu \rightarrow e\gamma$ experiment[12] enabled this group to identify the leading problems and to devise methods to solve them so as to perform a more sensitive experiment. In particular, the time resolution and energy resolution of the NaI have been substantially improved. This experiment should take data in 1983.

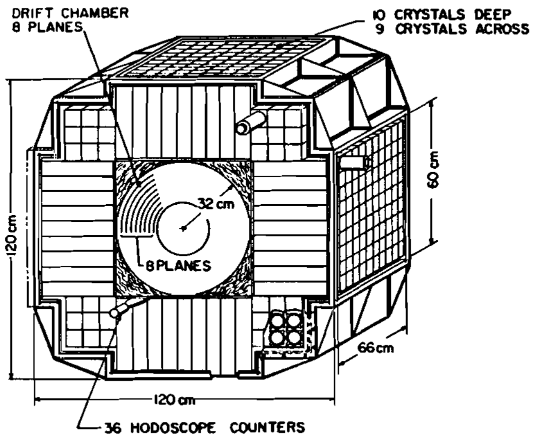

Fig. 1. Apparatus for the Crystal Box Experiment.

TABLE II
Crystal Box Experiment

Quantity	Value
$\frac{\Omega}{4\pi}$ ($\mu \rightarrow e\gamma$)	0.6
$\frac{\Omega}{4\pi}$ ($\mu \rightarrow eee$)	0.2
Muon stopping rate	5×10^5/s (average)
$\frac{\Delta E}{E}$	0.06 (FWHM)
Δt	0.7 ns (FWHM)
$\Delta\theta_\gamma$	~80 mr (FWHM)
Sensitivity	$\lesssim 10^{-11}$

At the conclusion of the Crystal Box experiment, the same group plans to reconfigure the NaI for γ detection and use a 180° magnetic spectrometer to detect the e^+ (Fig. 2). In this way, a sensitivity of $<10^{-12}$ is expected.[14] The parameters of this experiment are presented in Table III. It is not clear at this time how to design an experiment with still greater sensitivity. One certainly should draw on the experience gained in these next rounds of experiments. Clearly, higher muon intensities (at 100% duty factor) would help; this intensity could be used to achieve a smaller beam spot or to offset a limited solid angle in a higher resolution, more highly segmented detector.

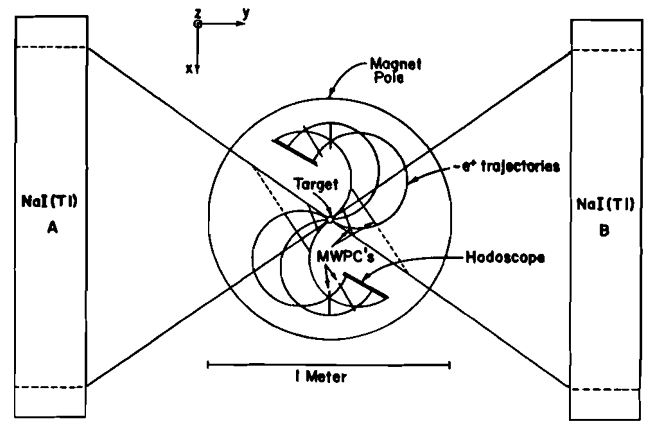

Fig. 2. Layout for the proposed LAMPF $\mu \rightarrow e\gamma$ Experiment.

TABLE III
LAMPF $\mu \rightarrow e\gamma_{II}$ Experiment

Quantity	Value
$\Omega/4\pi$	0.16
$\Delta E_\gamma/E_\gamma$	0.04 (FWHM)
$\Delta E_e/E_e$	0.006 (FWHM)
Δt	0.7 ns (FWHM)
$\Delta\theta_{e\gamma}$	20 mr (FWHM)
μ/s	$\approx 10^7$/s
Sensitivity	$\lesssim 10^{-12}$

Experiments are planned to improve the sensitivity to other muon-number-violating processes. The Crystal Box experiment[13] expects to be sensitive to $\mu^+ \rightarrow e^+e^+e^-$ and $\mu^+ \rightarrow e^+\gamma\gamma$ at the 10^{-11} level. The SINDRUM experiment at SIN[15] will use a cylindrical wire chamber in a magnetic field to search for $\mu^+ \rightarrow e^+e^+e^-$ with a sensitivity to a branching ratio as small as 10^{-12}. Two experiments are planned to search for $\mu^-Z \rightarrow e^-Z$ at the 10^{-12} level. The time-projection-chamber (TPC) experiment at TRIUMF[16] should be collecting data this year, but an experiment at LAMPF[17] probably will not run until 1984.

We see that the next round or two of the muon-number-violating processes with muons in the initial state are well advanced; the situation is summarized in Table IV. We will have to wait for the results of these experiments to know how to improve them further, although higher muon intensities will ultimately be crucial. There are plans to install a surface muon beam at the Alternating Gradient Synchrotron (AGS). Because one might expect more surface muons per incident proton at higher energies, it may turn out that a higher intensity 10- to 30-GeV proton synchrotron[18] will provide the largest muon flux.

TABLE IV
Summary of Upcoming Experiments

Process	Experiment	Sensitivity	Date of Experiment
$\mu^+ \to e^+\gamma$	Crystal Box	10^{-11}	1983
	LAMPF $\mu e\gamma_{II}$	10^{-12}	1985
$\mu^+ \to e^+e^+e^-$	Crystal Box	10^{-11}	1983
	SINDRUM	10^{-12}	1984
$\mu^+ \to e^+\gamma\gamma$	Crystal Box	10^{-11}	1983
$\mu^- Z \to e^- Z$	TRIUMF TPC	10^{-12}	1982-3
	LAMPF-Yale	10^{-12}	1984

Muon-number violation mediated by horizontal interactions, for example, may be most accessible in strangeness-changing decays such as $K_L^0 \to \mu e$, $K^+ \to \pi^+\mu^\pm e^\mp$, and $\Sigma^+ \to p\mu e$. The experimental situation here is less clear as the existing limits are by-products of other measurements; no one has performed an experiment designed to search for any of these processes. The existing limits are shown in Table V. Perhaps one should be circumspect about the $K_L^0 \to \mu e$ limit, as it was obtained in an experiment that did not observe $K_L^0 \to \mu^+\mu^-$ with a supposed sensitivity well below the now-established $K_L^0 \to \mu^+\mu^-$ rate. There is an approved AGS experiment to search for $K^+ \to \pi^+\mu^+e^-$ (but not $K^+ \to \pi^+\mu^-e^+$) at the 10^{-11} level.[19] This experiment is forced to use a short unseparated beam to obtain $\sim 10^7$ K^+/s. The $\approx 20/1$ π/K ratio, and backgrounds caused by muons penetrating the shielding, may limit the experiment. It is also important to note that $\Gamma(K^+ \to \pi^+\mu^+e^-) \neq \Gamma(K^+ \to \pi^+\mu^-e^+)$, in general; whichever rate dominates is model dependent. There is no plan at present to search for $K^+ \to \pi^+\mu^-e^+$.

TABLE V
Limits on Stangeness-Changing, Lepton-Flavor-Violating Decays

Process	Value (90% CL)	Reference
$\Gamma(K_L \to \mu e)/\Gamma(K_L \to \text{all})$	$<2 \times 10^{-9}$	A. Clark et al., Phys. Rev. Lett. 26, 1667 (1971).
$\Gamma(K^+ \to \pi^+\mu e)/\Gamma(K^+ \to \text{all})$	$<7 \times 10^{-9}$	A. M. Diamant-Berger et al., Phys. Lett. 62B 485 (1976).

Two groups would like to search for $K_L^0 \to \mu e$: a Yale group at the AGS[20] and a group at KEK.[21] Both groups expect to see branching ratios as small as 10^{-10}. The KEK group would like to take data before the 1984 shutdown there. The plans of the Yale group are less clear, as they are currently involved in a $K_L^0 \to \pi^0\pi^0$ experiment.

It is unclear what factors will ultimately limit these rare-kaon-decay experiments. The poor beam quality (π^+'s in the K^+ beam, neutrons in the K_L^0 beam, large beam spots, etc.) will certainly cause problems. Any attempt to further improve the sensitivities of these experiments undoubtedly would require more intense, higher quality kaon beams. These could be available at higher intensity synchrotrons.[18] With such a machine, one might see the same type of improvements for the rare-kaon-decay experiments as occurred at the meson factories for rare-muon-decay experiments.

The decay $\Sigma^+ \to p\mu e$ can only be studied in a positive hyperon beam; the proton from Σ^+ decay at rest is practically unobservable. The only such hyperon beam is at Fermilab. It has been estimated that a branching ratio as small as 10^{-11} could be detected there,[5] although no discussion of possible backgrounds (such as $\Sigma^+ \to \Lambda e^+\nu$, $\Lambda \to p\mu^-\nu$) was given.

A search for lepton-flavor-violating τ decays[22] has set upper limits at $\approx 5 \times 10^{-4}$. The sensitivity of these measurements is entirely determined by the number of available τ's. There is no apparent way to greatly increase this sample at present.

It is instructive to investigate whether significant information about lepton-flavor violation can be learned in high-energy interactions. Consider, for example, $e^+e^- \to \mu e$.[23] Because one would expect an effective four-Fermi interaction, the cross section should be proportional to s. Assuming that the lepton-flavor violation is characterized by a coupling constant G_x, we find

$$\frac{\sigma_{ee \to \mu e}}{BR(\mu^+ \to e^+e^+e^-)} \approx \frac{G_x^2 s}{G_x^2/G_F^2} = sG_F^2 \quad .$$

Because we already know that $BR(\mu^+ \to e^+e^+e^-) \lesssim 10^{-9}$, we would have to be able to detect

$$\sigma_{ee\to\mu e} \lesssim (sG_F^2)\,(10^{-9}) = 4 \times 10^{-43}\ \text{cm}^2 \qquad \text{for } s = 10^4\ \text{GeV}^2 \quad ,$$

which would imply an event rate of $\sim 4 \times 10^{-4}$ in 10^7 seconds at a luminosity of $10^{32}/\text{cm}^2\,\text{s}$. Clearly, the low-energy experiments are more sensitive to lepton-flavor violation.

The outlook for lepton-flavor violation appears to be improved sensitivities in the upcoming round of experiments. The muon-induced reactions are expected to reach sensitivities of $\sim 10^{-12}$; we will not know how to improve these experiments still further until we learn the lessons they have to offer. Still higher muon intensities with the highest possible duty factor ultimately will be required. The effort to study lepton-flavor violation in strangeness-changing decays is just beginning. The first-round experiments are trying to make do with poor-quality beams in order to obtain large kaon fluxes. Higher intensity proton machines will be required to produce the higher quality beams with the still higher fluxes that will be needed to achieve the best sensitivities possible.[24]

The discovery of lepton-flavor violation would indicate that the standard model is incomplete, or incorrect, and would cause a major upheaval in our view of physics. The search for this phenomenon must be pursued to as sensitive a level as possible in all possible reactions.

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$\Gamma(K_L \rightarrow \mu e)/\Gamma(K_L \rightarrow \text{all}) < 5 \times 10^{-16}$

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15. SINDRUM Experiment, H. C. Walter, Spokesman.

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