The Search for Muon-Number Violation at LAMPF

by Cy Hoffman and Minh Duong-Van

The ultimate goal of studies in nuclear and particle physics is to understand both the interactions between elementary particles and the structure of nuclei and particles. In the construction of a new theory, symmetry principles provide guidelines that must be followed. Noether's Theorem[1] tells us that whenever a physical process is invariant under a certain symmetry, there exists a corresponding conservation law. Thus, conservation of momentum follows from the invariance of physical laws under spatial translations; that is, there are no preferred positions in space. Conservation of energy follows from the invariance to time displacements; that is, there are no preferred moments in time. For a quantum mechanical system, such as a nucleus or a particle, the state of the system is characterized by certain quantum numbers corresponding to the values of conserved quantities. Some of these quantum numbers, such as electric charge and baryon number, do not change; others, such as angular momentum and strangeness, change only by discrete amounts as governed by selection rules. The discovery of a selection rule prompts us to search for the underlying symmetry principle.

In the past 25 years, we have learned that symmetries are not always universally valid. For example, the weak interaction (responsible for β decay, for example, $n \rightarrow p + e^- + \bar{\nu}$) violates invariance with respect to both parity (the symmetry between a system and its mirror image) and charge conjugation (the symmetry between matter and antimatter). The interaction responsible for the decay of the neutral K meson is not invariant under time reversal. In this article, we describe some origins of the law of conservation of lepton number and some efforts of physicists at LAMPF (the Los Alamos Clinton P. Anderson Meson Physics Facility) to search for violations of this law.

The muon was discovered in 1937[2] by exposing emulsion plates to cosmic rays. It was first thought to be Yukawa's meson,[3] the pi meson, which was predicted to mediate the strong interaction binding the nucleus together. However, it became clear that the muon interacted too weakly with matter to be the pi meson. The existence of the muon was neither predicted nor theoretically expected and since then, according to Feynman, "No one is quite sure what to do with the muon."[4]

The muon (μ) is an unstable particle that decays through the weak interaction into an electron (e), a neutrino (ν), and an antineutrino ($\bar{\nu}$): $\mu \rightarrow e + \nu + \bar{\nu}$. Historically, other possible decays into an electron and a photon (γ) or into three electrons ($\mu^+ \rightarrow \epsilon^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$) and the capture process ($\mu^- + Z \rightarrow e^- + Z$) were of great interest.[5] In the 1950s, it was believed that the muon and the electron were both leptons (light particles) with the same quantum numbers, a condition that allowed these processes to exist. The process $\mu^+ \rightarrow e^+\gamma$ is not allowed in the first-order approximation to the four-fermion theory of weak interactions in which four fermions (spin 1/2 particles, such as the electron, muon, and neutrino) can interact at a single point. However, the process is allowed in the second-order approximation by a more complicated virtual sequence of interactions. The branching ratio (ratio of decay rates) predicted by this model for the rare decay $\mu \rightarrow e\gamma$ versus the known decay $\mu \rightarrow e\nu\bar{\nu}$ was

$$\frac{\Gamma(\mu^+ \rightarrow e^+\gamma)}{\Gamma(\mu^+ \rightarrow e\nu\bar{\nu})} \sim 10^{-7},$$

where Γ is the rate for the process. In 1957, the experimental upper limit[6] for this branching ratio was $<2 \times 10^{-5}$; therefore, there was no discrepancy between theory and experiment.

However, as had long been realized,[7] the four-fermion weak interaction increases in strength with energy, leading to infinite answers. To avoid high-energy problems, Schwinger[8] conjectured that an intermediate vector boson (a particle with spin 1) mediates the weak interaction. In this nonlocal interaction, the branching ratio above is calculated to be $\sim 10^{-4}$, [5,9] in contradiction to the experimental limit. To reconcile this problem, the notion of lepton quantum number conservation was postulated.[8,10] In this scheme, assignments of lepton and muon numbers are made for the muon, the electron, and two kinds of neutrinos. These are shown in Table I. The conservation law then states that the sum of the lepton number and the sum of the muon number are each conserved separately. This law then forbids the unobserved processes, $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$, and $\mu^- + Z \rightarrow e^- + Z$, but allows all observed processes including $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$.

This scheme, however, requires the existence of distinct electron-neutrinos (ν_e) and muon-neutrinos (ν_μ). Pontecorvo and Schwartz[11] discussed methods to determine if there are two kinds of neutrinos. Danby et al.[12] performed the two-neutrino experiment in 1962 and showed that the neutrinos produced in pion decay, by the process

$$\pi^+ \rightarrow \mu^+\nu_\mu,$$

interacted with matter to produce muons by

$$\nu_\mu + n \rightarrow p + \mu^-,$$

but did not produce electrons. The neutrinos produced in beta decay ($N \rightarrow N' + e^- + \bar{\nu}$) do interact with matter to produce electrons.[13] This observation of two distinct types of neutrinos was seen as a validation of the lepton number conservation law.

TABLE I ASSIGNMENTS

Lepton Number Assignment

Particle	Lepton Number
$e^-, \mu^-, \nu_e, \nu_\mu$	+1
$e^+, \mu^+, \bar{\nu}_e, \bar{\nu}_\mu$	−1
All others	0

Muon Number Assignment

Particle	Muon Number
μ^-, ν_μ	+1
$\mu^+, \bar{\nu}_\mu$	−1
All others	0

The experimental status of muon number conservation in 1964 and 1980 is shown in Table II. The prevailing attitude after the two-neutrino experiment was expressed as follows:

> The results of the neutrino experiments . . . indicate that the normal weak interaction channels are closed to this decay mode [$\mu \rightarrow e\gamma$]. Since it now appears unlikely that this decay is lurking just beyond present experimental resolution, any further search for the $\mu \rightarrow e\gamma$ decay mode at this time seems futile.[14]

Even though lepton number conservation accounts for the failure to detect the processes in Table II, there is no fundamental reason for this conservation law to be exact. Unlike electric charge

TABLE II
STATUS OF MUON NUMBER CONSERVATION, 1964 AND 1980

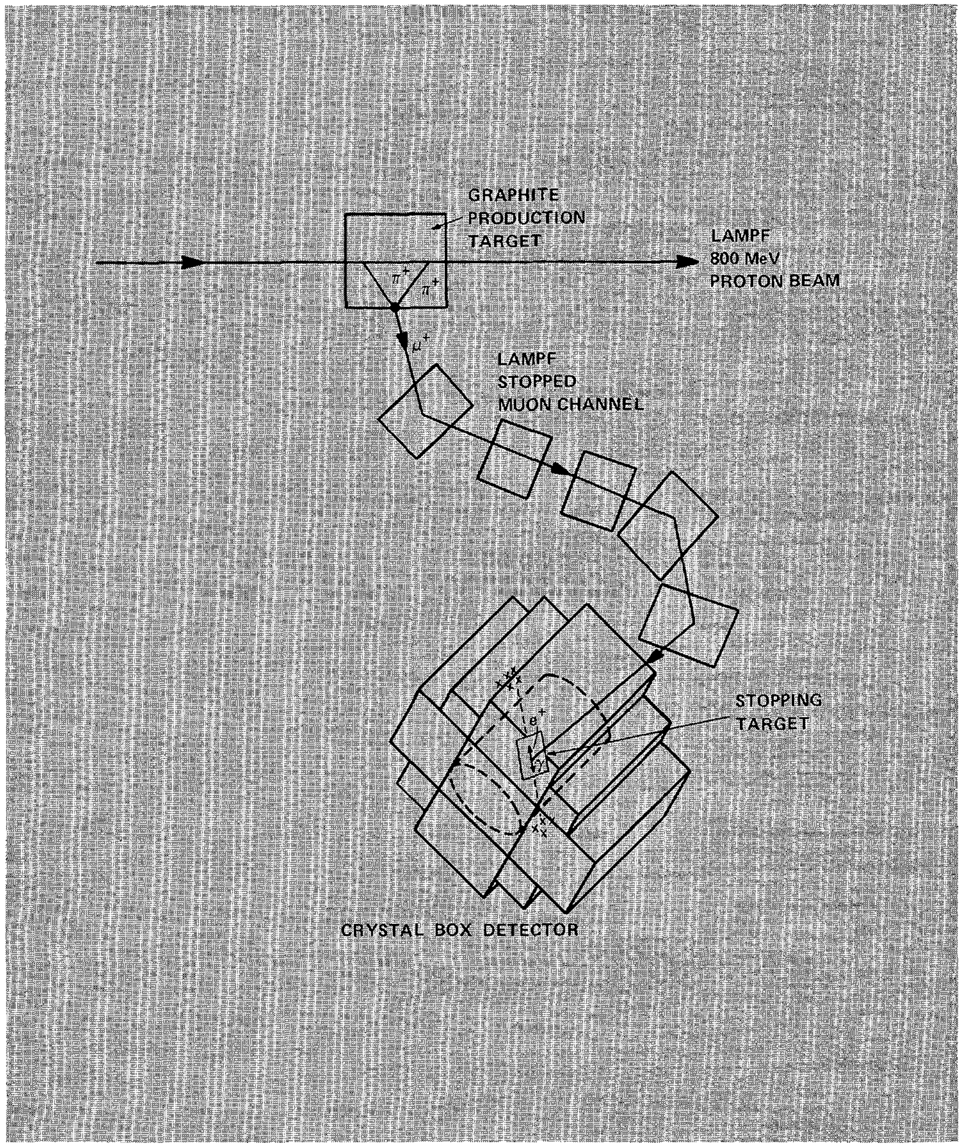
Muon Number Process	1964	1980
$\frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e\nu\bar{\nu})}$	$<2.2 \times 10^{-8}$	$<1.9 \times 10^{-10}$
$\frac{\Gamma(\mu \rightarrow eee)}{\Gamma(\mu \rightarrow e\nu\bar{\nu})}$	$<1.3 \times 10^{-7}$	$<1.9 \times 10^{-9}$
$\frac{\Gamma(\mu^- Z \rightarrow e^- Z)}{\Gamma(\mu^- Z \rightarrow \nu Z')}$	$<2.4 \times 10^{-7}$	$<7 \times 10^{-11}$
$\frac{\Gamma(\mu \rightarrow e\gamma\gamma)}{\Gamma(\mu \rightarrow e\nu\bar{\nu})}$	$<1.6 \times 10^{-5}$	$<5 \times 10^{-8}$

conservation, which must be exact by virtue of the gauge invariance of the electromagnetic field whose quantum excitations are massless photons, lepton number conservation is not associated with a massless gauge field. A heuristic argument[15] will help explain this.

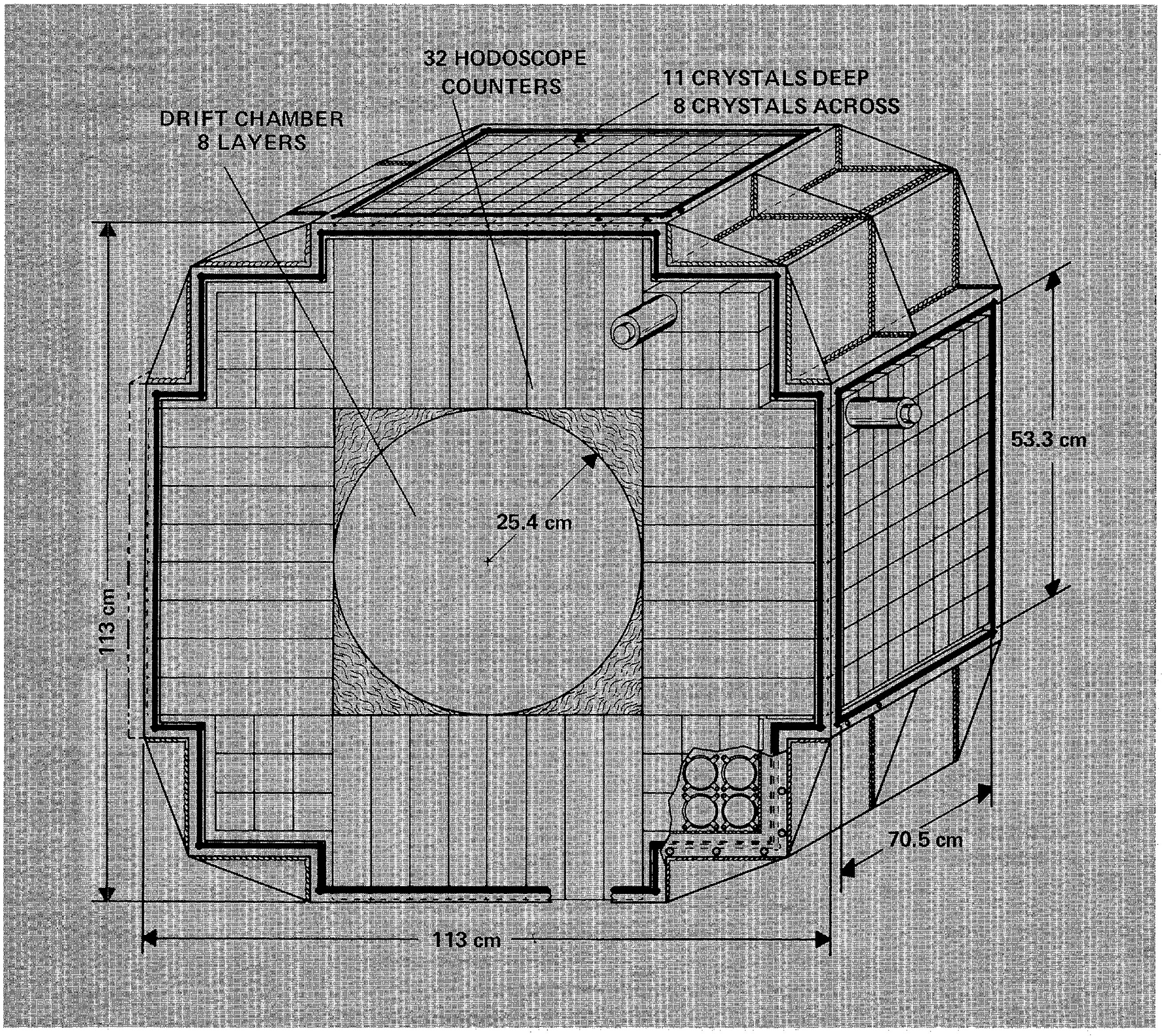
Assume that black holes exist. If a charged particle falls into a black hole, the memory of its charge is preserved by its electric field outside the black hole, so that conservation of electric charge can be verified. On the other hand, if a muon-neutrino falls into the black hole, it leaves no trace at all, so that an exact conservation law for muon number is not a measurable concept.

The most exciting development of the past decade in theoretical physics has been the successful unification of the weak and electromagnetic interactions within the framework of non-Abelian gauge theories.[16] (Electromagnetic interactions alone are described by the Abelian gauge theory quantum electrodynamics.) At present, there is considerable latitude in the exact composition and structure of the correct gauge model: this freedom can be reduced only by accumulating more experimental facts. The gauge models not only suggest that lepton number conservation is not exact, they also predict that muon-number violating processes may occur at rates somewhat below experimental limits. If we can measure the rates or reduce the experimental limits, we will go a long way toward pinning down the correct unified model of weak and electromagnetic interactions and place additional constraints on the many grand unified models recently proposed to unify the weak, electromagnetic, *and strong* interactions.

In 1977, a group of physicists from the Los Alamos Scientific Laboratory, the University of Chicago, and Stanford



Schematic view of the experiment at LAMPF. The 800-MeV proton beam strikes a graphite production target producing pions. Some π^+'s slow down and stop near the surface of the target and decay into μ^+'s. The muons are then transported by the stopped muon channel to the detection apparatus: The channel consists of dipole bending magnets and quadrupole focussing magnets. The muons come to rest in the stopping target in the center of the cyrstal box detector and then decay. A $\mu^+ \rightarrow e^+\gamma$ event is shown. Positrons and electrons are detected in the drift chamber and hodoscope counters and their energy is measured in the NaI: photons do not register in either the drift chamber or the hodoscope counters but do deposit energy in the NaI. All information from the detectors is processed by an on-line computer and stored on magnetic tape for further off-line analysis.



The crystal box that will be used to detect rare decays of the muon.

University[17] mounted an experiment at LAMPF to search for the decay $\mu^+ \rightarrow e^+\gamma$. The high-intensity beams of muons available at LAMPF are particularly well suited to a search for this rare decay. This experiment did not detect the decay but did push the experimental upper limit[17] down to

$$\frac{\Gamma(\mu^+ \rightarrow e^+\gamma)}{\Gamma(\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu)} < 1.9 \times 10^{-10} ,$$

about an order of magnitude more sensitive than any previous search.

Now a new collaboration from the same three institutions has embarked on an experiment to search for the muon-number violating processes $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$, and $\mu^+ \rightarrow e^+\gamma\gamma$ with a large new experimental facility known as the *crystal box*.

As shown in the conceptual drawing of the apparatus, the basic design of the detection system calls for a large solid-angle modular sodium iodide detector, weighing ~2000 kg, surrounding a thin target in which the muons stop and decay, a cylindrical drift chamber, and trigger hodoscope (plastic scintillation) counters. The approximately 400 sodium iodide modules will detect 53-MeV positrons and photons with essentially 100% efficiency, an energy resolution of ~2 MeV (FWHM) and a timing resolution of 0.5 ns (FWHM) (1 ns = 10^{-9} s). The drift chamber will record the passage of charged particles with a position resolution of ~200 μM (FWHM) in each of eight layers. Photons produced in the events will be identified by detecting energy deposited in the sodium iodide with no corresponding response from the drift chamber or hodoscope counters; electrons and positrons are detected by all of these systems.

The three processes, $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^+e^-$, and $\mu^+ \rightarrow e^+\gamma\gamma$, will be studied simultaneously with a sensitivity to branching ratios of about 10^{-11}. (This represents an improvement of ~10, 100, and 5000, respectively, over present experimental limits.) Events will be selected by a hard-wired processor designed to use both the analog and digital information from the detector and to make a decision within 250 ns.

This speed will enable the apparatus to operate at a flux of 5×10^5 μ^+/s and will provide an immediate suppression of accidental coincidences from the ordinary decays of several muons. We will begin setting up the experiment in late 1980 and will begin taking data by mid-1981.

If any of these processes is observed, it will be obvious evidence of the failure of the conservation of muon number. The strength of the failure will provide a great deal of information as to what is the correct model of the basic interactions. Should none of these processes be observed, the experiment will force tight constraints on many potential models and eliminate many others. If the process $\mu^+ \rightarrow e^+\gamma$ is not observed in the crystal box, we plan to reconfigure the sodium iodide modules inside a large magnet and continue the search for muon-number violation with at least an order of magnitude greater sensitivity.

The search for muon-number violation is being pursued at LAMPF with several orders of magnitude greater sensitivity than anywhere else in the world. It must be stressed that "theory" neither predicts nor forbids this violation. The outcome of these experiments will have a great bearing on the way we view the world. Perhaps one of the few conservation laws that we believed to be exact will turn out to be violated after all.


Cy Hoffman (left) and Minh Duong-Van (right) examine a prototype drift chamber, a component of the crystal box detector that will be used to search for rare decays of the muon.

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