Lawrence Berkeley National Laboratory
Recent Work

Title
MUON DECAY

Permalink
https://escholarship.org/uc/item/1jj4g491

Author
Steiner, H.

Publication Date
1985-03-01

eScholarship.org Powered by the California Digital Library
University of California

LBL-19684
c.2

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY

JUN 28 1985

LIBRARY AND
DOCUMENTS SECTION

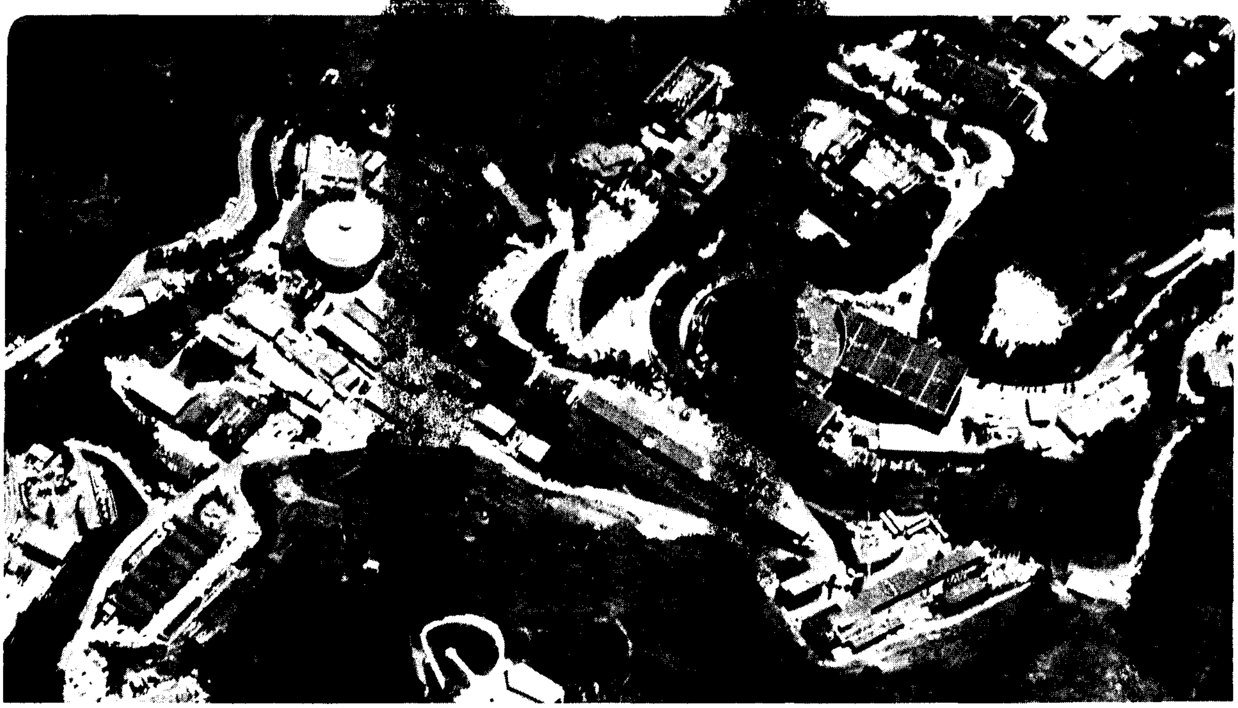
Physics Division

Presented at the XXth Rencontre de Moriond,
Fifth Moriond Workshop, La Plagne, France,
January 13-19, 1985

MUON DECAY

H. Steiner

March 1985



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-19684
c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-19684

MUON DECAY

Herbert Steiner
Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720, U.S.A.*

ABSTRACT

Improved searches for rare processes in muon decay have substantially improved existing limits, but no evidence for any non-standard behavior has been found. The result of a recent sensitive search for right-handed currents indicates that the ratio (V+A)-amplitude/(V-A)-amplitude $\leq$ 0.029. This experiment also imposed new limits on non-standard couplings and on the energy scales where lepton substructure and family symmetry breaking effects might manifest themselves.

Although muon decay has been studied extensively for more than 30 years there have been several interesting new experiments during the last year or two. I have chosen to subdivide these new experiments into two classes: (1) standard decay (e.g. $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$), where the objectives were to improve our understanding of the Lorentz structure of the interaction, to search for right handed currents, and to search for lepton substructure, and (2) searches for rare processes such as the decays $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^-e^+$, $\mu^+ \rightarrow e^+ + f$ (f is an axion-like scalar) and the conversion process $\mu^- + (A,Z) \rightarrow e^- + X$, where the goals were to explore new physics.

These and the other new results can be summarized by the somewhat disappointing statement that nothing unusual was seen. An LBL/TRIUMF/Northwestern collaboration found no evidence for right-handed currents. No evidence was seen for S, T or P couplings nor was there any indication that leptons have substructure below a composite mass scale of 2400 GeV. No experiment has found any evidence for any of the rare processes mentioned previously. The present limits on the relevant branching ratios are:

B.R. $(\mu^+ \rightarrow e^+e^-e^+) \leq 2.4\times10^{-12}$	(SIN)[2]
B.R. $(\mu^- + (A,Z) \rightarrow e^- + X) \leq 2\times10^{-11}$	(TRIUMF)[3]
B.R. $(\mu^+ \rightarrow e^+ + f) \leq 6\times10^{-6}$	(LBL/TRIUMF/NW)[4]
B.R. $(\mu^+ \rightarrow e^+ + \gamma) \leq 1.7\times10^{-10}$	(PDG World Average)

Despite the lack of unexpected new results it is important to realize that the frontiers continue to be pushed back significantly, and that possible subtle deviations from expectations based on the Standard Model may only manifest themselves experimentally as measurements of ever increased refinement and precision are made. I think the recent muon decay experiments constitute very meaningful steps in that direction. Other experiments at TRIUMF, LAMPF and SIN are underway to further improve this situation.

As an illustration of the present generation of muon decay experiments I would like to discuss in more detail our Search for Right-Handed Currents in Muon Decay at TRIUMF.[1] In particular I will present the current (essentially final) status of the results and discuss their significance in terms of right-handed currents, limits on non-(V,A) couplings, the existence of axion-like scalars, and lepton substructure.

When we embarked on this search all weak interaction experiments were consistent with a pure (V-A) interaction. They still are. However, an admixture of up to 13% (V+A)-amplitude also fit the data. Equivalently the right-handed gauge boson, W_R, had to be at least twice as massive as its standard left-handed counterpart, W_L. In the meantime, theoretical analysis of the K_1^0–K_2^0 mass difference strongly suggests that $M(W_R) > 1.6$ TeV.[5] However, such analyses are at least weakly model-dependent and therefore an independent measurement is useful. Furthermore, the only previous measurement made in the late 1960's yielded a result which was 2 standard deviations away from the pure V-A prediction.

The method used in our search was to study the decay $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$ for fully polarized muons when the positrons are emitted with maximum energy; i.e. when $x = p_e/p_e(\max) \cong 1$. One produces fully polarized μ^+ from pion decay at rest, stops them in a non-depolarizing target, and then looks for x = 1 positrons emitted in a direction opposite to that of the muon's spin. By angular momentum conservation these positrons must have negative helicity. This is forbidden for a pure (V-A)-interaction, and therefore any such positrons would signal the presence of a (V+A) interaction. Unfortunately the finite energy and angular acceptances of the apparatus allow tails of the (V-A) positron distributions to be detected as well, and suitable extrapolations are necessary to cleanly isolate the (V+A)-contribution.

The shape of the expected V-A spectrum is shown in figure 1. It can be written:

$$\frac{d^2\Gamma}{x^2dxd(\cos\theta)} \propto \left\{\left[(3\text{-}2x) + \left(\frac{4}{3}\rho\text{-}1\right)(4x\text{-}3) + 12\left(\frac{m_e}{m_\mu}\right)\left(\frac{1\text{-}x}{x}\right)\eta\right] + \left[(2x\text{-}1) + \left(\frac{4}{3}\delta\text{-}1\right)(4x\text{-}3)\right]\xi P_\mu\cos\theta\right\}.$$

Here $\pi-\theta$ is the angle between $\vec{S}_\mu$ and $\vec{p}_e$; ρ, η, δ, ξ are the usual muon decay parameters, and P_μ is the polarization of the muon.

$$\text{When } x = 1, \qquad \frac{d^2\Gamma}{dxd(\cos\theta)} \propto \left\{1 - \frac{\delta\xi}{\rho}P_\mu\cos\theta\right\}.$$

For a pure V-A interaction $\xi = 1$, $\rho = \delta = 3/4$, $P_\mu = 1$. When $\cos\theta = 1$ the rate vanishes. In the experiment we measure $P_\mu\delta\xi/\rho$. In a separate experiment with the same apparatus we were also able to make an improved measurement of the parameter δ.

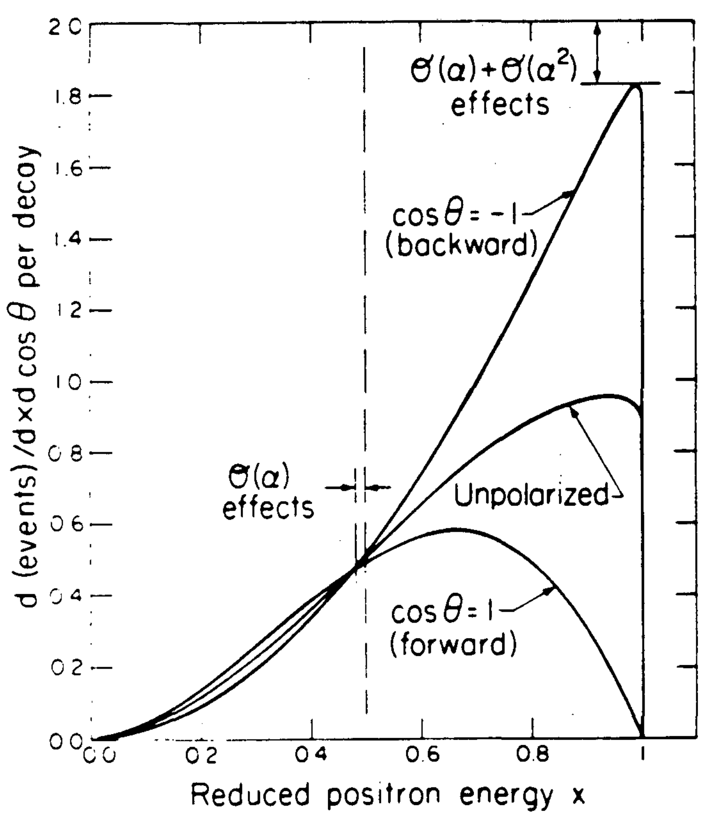


Fig. 1. Positron momentum spectrum from completely polarized μ^+ decay at rest for a V-A interaction.

The experimental method had three essential ingredients:

(1) *A 100% polarized μ^+ beam.* This was done by using the so-called surface muon beam at TRIUMF. The basic idea is to first produce positive pions with 500 MeV protons. The pions of interest stop and decay into muons near the surface of the production target. These fully polarized muons are then transported by a system of magnets and quadrupoles to the stopping target without depolarizing them.

(2) *Stopping the muons without depolarizing them.* To do this thin metal foil targets (Al, Au, Ag, Cu) were used. A longitudinal magnetic field, $B_{\parallel} \cong 1.1$T, was usually applied as an additional safeguard against depolarization. Alternatively the longitudinal field could be replaced by a weak transverse magnetic field ($B_{\perp} \sim 100$ gauss) which was used to precess the muon spins. The data taken in this mode were used both for purposes of calibrating the $x = 1$ edge of the decay spectrum and for a largely independent measurement of $P_\mu \xi \delta / \rho$ based on the magnitude of the μSR precession amplitude.

(3) *Determining the momentum and angle of the decay positron with good resolution.* To do this we used a focusing spectrometer with momentum resolution ($\Delta p/p \cong 0.002$). The absolute calibration of the spectrum end point was based on the spin precessed data discussed in (2).

The experiment is essentially complete. Preliminary results obtained with the longitudinal field configuration have been published,[6] and the more recent μSR analysis has been submitted for publication[7] and reported at last summer's Leipzig Conference.[4] An example of the shapes of the spin-held and spin-precessed data near $x = 1$ is shown in figure 2. The characteristic oscillations in the rate of detected positrons as a function of time for the μSR data is shown in figure 3. Here the exponential decay with μ^+ lifetime has been factored out.

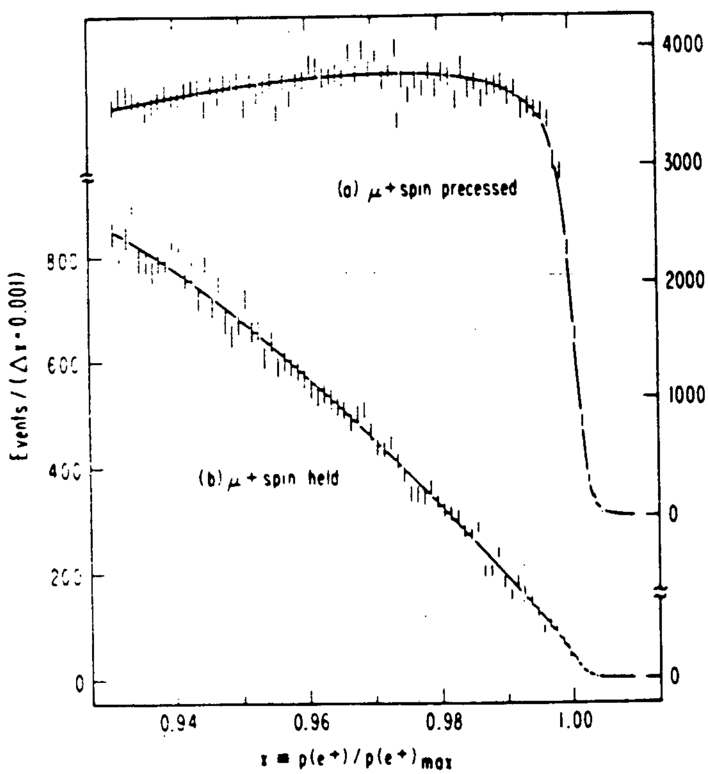


Fig. 2. Distributions (uncorrected for acceptance) in reduced positron momentum with the μ^+ spin (a) precessed and (b) held.

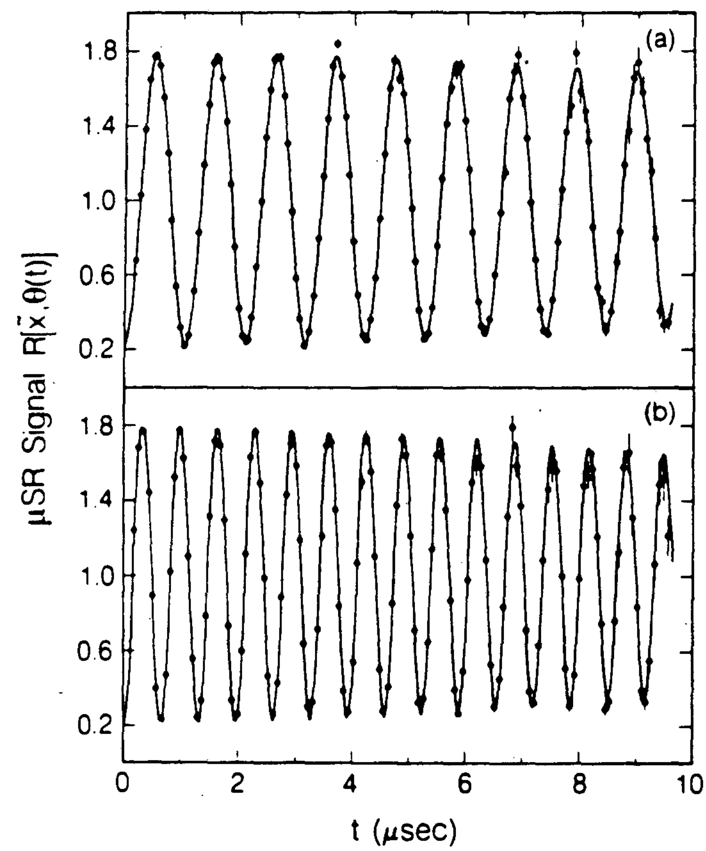


Fig. 3. Data constituting 73% of the total μSR data, with (a) 70-G, and (b) 110-G transverse fields.

In the space available here it is not possible nor appropriate to describe in further detail either the experimental method or the various systematic checks that played essential roles in these measurements. The interested reader is referred to the references just cited.[6,7]

Let me turn next to the results. It is important to note that the (V+A) limits obtained in this experiment are only valid if the mass of the heavy right-handed neutrino is less than about 10 MeV/c^2. Our result $P_\mu \xi \delta / \rho \geq 0.9966$ (90% CL) places the following limit on the contribution of a possible (V+A) interaction to muon decay:

$$\frac{\text{(V+A) Amplitude}}{\text{(V−A) Amplitude}} \leq 0.029 \qquad \text{(90\% CL)}.$$

In terms of mass limits on a right-handed gauge boson which could mediate such an interaction it is necessary to introduce two parameters--a mass and a mixing angle. This is because the mass eigenstates (W_1,W_2) are not necessarily the same as the charged gauge boson eigenstates (W_L,W_R).

Writing $W_1 = W_L \cos\varsigma - W_R \sin\varsigma$ and $W_2 = W_L \sin\varsigma + W_R \cos\varsigma$, we find $M(W_2) \geq 470$ GeV/c^2 if ς is constrained to be zero whereas $M(W_2) \geq 400$ GeV/c^2 if ς is free.

In general the Lorentz structure of the interaction admits the possibility of S, T, and P couplings in addition to the dominant V-A term. Let us write

$$L_{int} = -\frac{G}{\sqrt{2}} \sum_{i=1}^{5} [(\bar{e}\Gamma_i \nu_e)(\bar{\nu}_\mu \Gamma_i (G_i + G_i' \gamma_5)\mu) + \text{h.c.}] \qquad \text{where } \Gamma_i = 1,\ \gamma_\alpha,\ \sigma_{\alpha\beta},\ \gamma_\alpha\gamma_5,\ i\gamma_5.$$

Then the results of this experiment can be used to obtain the following limits:

(1) If the interaction is (V–A) + T (no S and P) $(G_T + G_T')^2 \leq 0.027$.

(2) If the interaction is (V–A) + S + P (no T) $(G_S - G_{P'})^2 + (G_S' - G_P)^2 \leq 0.054$.

With the same apparatus we obtained an improved value for the muon decay parameter δ. If only (V,A) couplings contribute to muon decay $\delta = 3/4$. Deviation from this value would signal something new, and can be used to further constrain S, T, and P contributions. Our very preliminary result is

$$\delta = 0.748 \pm 0.004 \text{ (statistical)} \pm 0.003 \text{ (systematic)}.$$

This should be compared with the world average value $\delta = 0.755 \pm 0.009$ listed in the latest Particle Data Group compilation.

The fact that our value of $P_\mu \xi\delta/\rho$ is very close to 1 can be used to set a limit on the mass scale above which composite lepton structure might manifest itself.[8] If leptons are composite there should be a contact interaction contribution to the Lagrangian describing muon decay. Following Peskin let us write

$$L = L_{V-A} + L_{contact}$$

where L_{V-A} is the usual V-A Lagrangian, and

$$\begin{aligned} L_{contact} = g^2/\Lambda^2\{ \; & \eta_1(\overline{\nu}_{\mu_L}\gamma^\mu \mu_L)(\overline{e}_L\gamma_\mu \nu_{e_L}) + \eta_2(\overline{\nu}_{\mu_R}\gamma^\mu \mu_R)(\overline{e}_R\gamma_\mu \nu_{e_R}) + \eta_3(\overline{\nu}_{\mu_L}\gamma^\mu \nu_{e_L})(\overline{e}_R\gamma_\mu \mu_R) \\ + \; & \eta_4(\overline{e}_L\gamma^\mu \mu_L)(\overline{\nu}_{\mu_R}\gamma_\mu \nu_{e_R}) + \eta_5(\overline{\nu}_{\mu_L}\mu_R)(\overline{e}_L\nu_{e_R}) + \eta_6(\overline{\nu}_{\mu_L}\nu_{e_R})(\overline{e}_L\mu_R) \\ + \; & \eta_7(\overline{\nu}_{\mu_R}\mu_L)(\overline{e}_R\nu_{e_L}) + \eta_8(\overline{\nu}_{\mu_R}\nu_{e_L})(\overline{e}_R\mu_L)\} \end{aligned}$$

Here g is a coupling constant of hadronic strength, Λ is the mass scale for compositeness, and the η_i are couplings of order unity. This is the most general SU(2)×U(1) invariant contact interaction. Using this Lagrangian to calculate the decay rate near x = 1 and $\cos\theta = +1$ we find

$$1 - \frac{\xi\delta}{\rho} P_\mu = 2\left(\frac{620}{\Lambda}\right)^4 \frac{g^2}{4\pi}\left(\eta_2^2 + \eta_3^2 + \frac{\eta_5{}^2}{4}\right) \leq 0.0034$$

or that $\Lambda^2 > (3050 \text{ GeV})^2 \frac{g^2}{4\pi}\left(\eta_2^2 + \eta_3^2 + \frac{\eta_5{}^2}{4}\right)$. If we make the not unreasonable assumption that $\frac{g^2}{4\pi} = 2.1$ and $\eta_i > 0.2$, then $\Lambda \geq 2400$ GeV. This value of Λ should be compared with limits deduced from other experiments using the same kind of model:

Experiment	Λ lower limit
$(g-2)_e$	~ 30 GeV
$(g-2)_\mu$	~ 750 GeV
$e^+e^- \rightarrow e^+e^-$	~ 2000 GeV

Finally we use the vanishing of the rate at x = 1 and $\cos\theta = +1$ to set a limit on the energy scale at which flavor symmetry could be spontaneously broken. The specific familon model discussed here is due to Wilczek.[9] Suppose muons could decay via the mode $\mu^+ \rightarrow e^+ + f_{\mu e}$, where $f_{\mu e}$

is an axion-like scalar called the familon. The contribution to the Lagrangian can be written:

$$\Delta L = \frac{1}{F_{\mu e}} \bar{\mu}\gamma_\rho e \partial_\rho f_{\mu e}.$$

and the branching ratio is

$$\frac{\Gamma(\mu^+ \to e^+ + f)}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \cong \frac{2.5\times 10^{14}}{F^2_{\mu e}} (\mathrm{GeV})^2.$$

Here $F_{\mu e}$ is the energy scale at which flavor symmetry is spontaneously broken.

Because $\mu^+ \to e^+ + f$ is isotropic it should cause monoenergetic positrons to be emitted at $x = 1$ and $\cos\theta = 1$. We see no such peak, and consequently set the limit:

$$\frac{\Gamma(\mu^+ \to e^+ + f)}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \leq 6\times 10^{-6}.$$

This translates to $F_{\mu e} \geq 6.5\times 10^9$ GeV (90% CL).

I think this example illustrates how muon decay experiments address a variety of issues of current interest in particle physics. It would be nice if one of these days a new generation of even more refined measurements would actually show some unpredicted behavior and thereby allow us to probe the next level of understanding of elementary processes.

REFERENCES

* This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under contracts DE-AC03-76SF00098 and AC02-ER02289.

1) Berkeley-LBL/Northwestern/TRIUMF Collaboration: B. Balke, J. Carr, G. Gidal, B. Gobbi, A. Jodidio, C.J. Oram, K.A. Shinsky, H.M. Steiner, D.P. Stoker, M. Strovink, and R.D. Tripp.

2) H.K. Walter, ETHZ-IMP-P84/4, August 1984 (unpublished), invited talk at 10th Int. Conf. on Particles and Nuclei (PANIC), Heidelberg, West Germany, July 30 - August 3, 1984.

3) D.A. Bryman et al., TRI-PP-84-59, July 1984 (unpublished), invited talk at 10th Int. Conf. on Particles and Nuclei (PANIC), Heidelberg, West Germany, July 30 - August 3, 1984.

4) B. Balke et al., "Search for Right-Handed currents in Muon Decay", contribution to XXII Int. Conf. on High Energy Physics, Leipzig, East Germany, July 19-25, 1984.

5) G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. **48,** 848 (1982).

6) J. Carr et al., Phys. Rev. Lett. **51,** 627 (1983).

7) D.P. Stoker et al., "Search for Right-Handed Currents Using Muon Spin Rotation", LBL-18935, submitted for publication.

8) M.E. Peskin, private communication.

9) F. Wilczek, Phys. Rev. Lett. **49,** 1549 (1982).

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720