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POSSIBLE DEVIATIONS FROM (V-A) CHARGED CURRENTS: PRECISE MEASUREMENT OF MUON DECAY PARAMETERS

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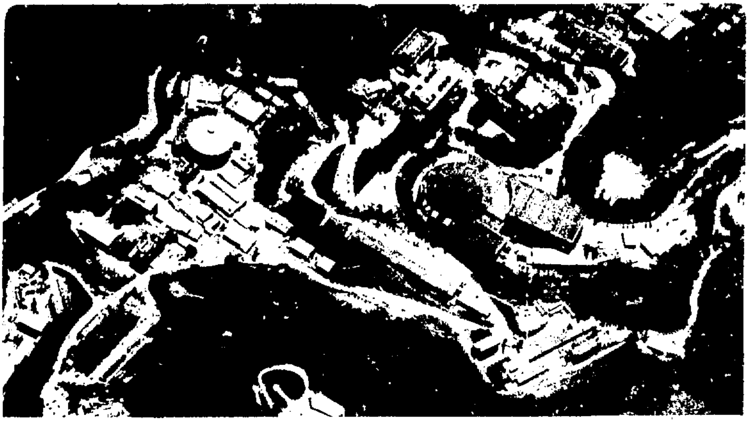
February 1981



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Possible Deviations from (V-A) Charged Currents: Precise Measurement of Muon Decay Parameters

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POSSIBLE DEVIATIONS FROM (V-A) CHARGED CURRENTS: PRECISE MEASUREMENT OF MUON DECAY PARAMETERS

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INTRODUCTION

This short review examines the experimental limits on possible deviations from (V-A) charged weak currents, as would occur at some mass scale, for example, in manifestly left-right-symmetric electroweak theories. I shall consider both present and anticipated limits, emphasizing muon-decay experiments but including other experimental input where convenient.

At the outset, I shall take this opportunity to present a slightly pertinent result from the Berkeley-Fermilab-Princeton muon-scattering group [1], who obtain limits on the mass of a possible *neutral* muon which couples to right-handed currents. Turning to the parameters describing muon decay, I shall summarize too briefly the already precise experimental results of the 1960's. The major new experimental input to this field, nearly dormant through the last decade, is the measurement of longitudinal and transverse polarization of decay positrons performed by the ETH/Zurich-SIN-Mainz group at SIN [2]. After describing their results I shall mention several of the new experiments aiming to push further the measurement of muon decay parameters. Technologically, the most ambitious new effort is the Time Projection Chamber at LAMPF, under construction by the Los Alamos-Chicago-NRC/Canada-Carleton group. It is described in detail by J.D. Bowman in his contribution to these Proceedings. After brief remarks on the effects of possible charged Higgs boson exchange, I shall conclude by discussing present and possible future experimental constraints on the existance of a right-handed gauge boson W_R.

I. MASS LIMITS ON A HEAVY NEUTRAL MUON

The limit has recently been published[3] by the Berkeley-Fermilab-Princeton muon experiment, based on a 1978 exposure to the now-extinct Fermilab muon beam. The apparatus, shown in Fig. 1, used a distributed magnetized-steel calorimeter for high luminosity and efficient identification of muons in the final state. During the course of this experiment, the study of lepto-produced "extra" final-state muons progressed from observation of a few tens of multi-muon events to quantitative study of high-statistics samples -- in this case, some 10^5 events with two muons in the final state, due primarily to charmed-quark-pair production followed by semileptonic decay.

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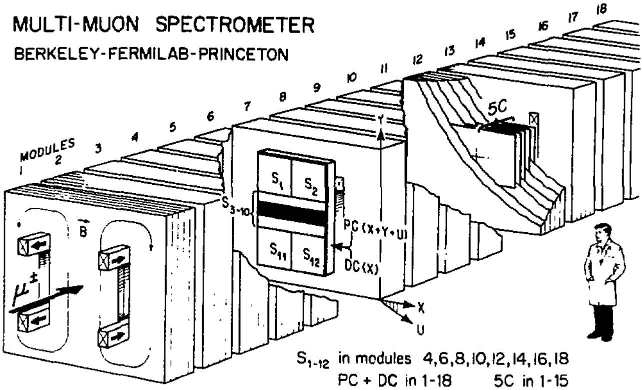

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Fig. 1. Sketch of the Berkeley-Fermilab-Princeton multimuon spectrometer. The spectrometer magnet, serving also as a target and hadron absorber, reaches 19.7 kG within a $1.8\times1\times16\text{-m}^3$ fiducial volume. Over the central $1.4\times1\times16\ m^3$, the magnetic field is uniform to 3% and mapped to 0.2%. Eighteen pairs of proportional (PC) and drift chambers (DC), fully sensitive over $1.8\times1\ m^2$, determine the muon momenta typically to 8%. The PC's register coordinates at 30^o (u) and 90^o (y) to the bend direction (x) by means of 0.5-cm-wide cathode strips. Banks of trigger scintillators (S_1-S_{12}) occupy eight of the eighteen magnet modules. Interleaved with the 10-cm thick magnet plates in modules 1-15 are 75 calorimeter scintillators resolving hadron energy E_{had} with rms uncertainty $1.5E_{had}^{1/2}$ GeV. Not shown upstream of module 1 are 1 PC and DC, 63 beam scintillators, 8 beam PC's, and 94 scintillators sensitive to accidental beam and halo muons.

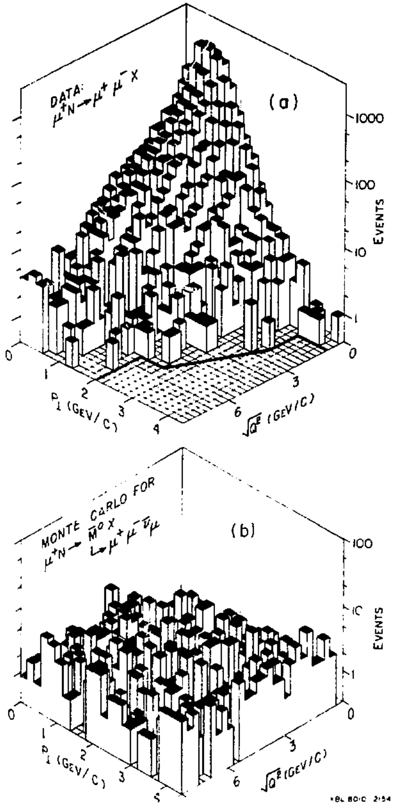

Fig. 2. Two-dimensional distributions of dimuon-final-state events vs. $\sqrt{Q^2}$ and $p_\perp$, the daughter muon momentum transverse to $\vec{Q}$. For this analysis, Q^2 is defined by taking the highest-energy beam-sign final state muon to be a scattered beam muon. The vertical scale is logarithmic; bin populations range from 0 to 450. Distribution (a) shows the data and an empirically chosen contour within which these events are contained. Distribution (b) is 77.4× the simulated population from production and decay of a 6 GeV/c^2 $\bar{M}^0$, with the assumptions described in the text. The 3.5 events in (b) lying outside the contour in (a) give the quoted σB limit at this mass.

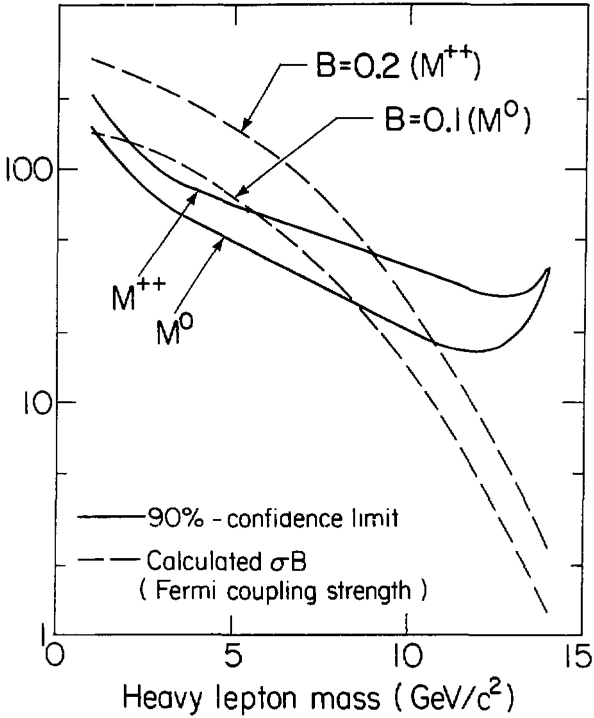

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Fig. 3. Mass-dependent limits on the product of cross section and $\mu\mu\nu$ branching ratio (σB) for $\bar{M}^0$ and M^{++} production. Also indicated are the calculated σB for the production of $\bar{M}^0$'s and M^{++}'s, where the branching ratio is assumed to be 0.1 and 0.2 for $\bar{M}^0$ and M^{++}, respectively. To 90% confidence the data exclude the production of an $\bar{M}^0$ or M^{++} coupled with Fermi strength to a right-handed current in the mass range $1<m_M<9$ GeV/c^2.

A primary motivation for the search for a heavy neutral muon (M^0) had been the "hybrid" gauge model which placed the M^0 in a right-handed doublet with the μ^-. In the electron sector, this model has since been ruled out by the polarized-electron scattering experiments at SLAC[4]. Nevertheless, the M^0 has surfaced from time to time in other gauge models [5,6] which are not yet phenomenologically defunct. In most cases, the M^0 is made to couple with near Fermi strength to muons via a right-handed current. This is a good match to the large "unnatural" polarization of muon beams derived from forward π decay. The Berkeley-Fermilab-Princeton group searched for the reaction

$$\mu^+(\mathrm{L.H.})N \to \bar{M}^0 X;\ \bar{M}^0 \to \mu^+\mu^-\bar{\nu}_\mu .$$

The two-muon-final-state signature is shared by "background" processes like charm or other hadron production with a subsequent decay into μ^-.

After various cuts were applied to enhance the sensitivity to $\bar{M}^0$ events relative to background, the data were analyzed as though the final-state μ^+ were a scattered beam muon, and accumulated on a two-dimensional histogram (Fig. 2) of $\sqrt{Q^2}$ vs. $p_\perp$, the μ^- momentum transverse to $\vec{Q}$. The background (Fig. 2(a)) has low Q^2 because of the photon propagator, and low $p_\perp$ because of the small charmed quark mass. Using a standard parton model with logarithmic scale-noninvariance, the simulated $\bar{M}^0$ events are found to have larger Q^2 and $p_\perp$, because of the W_R propagator and the higher $\bar{M}^0$ mass (6 GeV/c^2 in Fig. 2(b)). Simulated $\bar{M}^0$ populations in the background-free region result in the mass-dependent 90%-confidence limits on σB plotted in Fig. 3. For M^0 production, these lie below the levels expected for $B=0.1$ and Fermi coupling strength in the M^0 mass interval $1<M(M^0)<9$ GeV/c^2. No comparable experimental information on the M^0 exists in this mass range. In fact, I am unaware of another experiment outside a neutrino beam which has been sensitive, on an event-by-event basis, to any weak production process.

II. MUON DECAY EXPERIMENTS

A. Baroque Era

Figure 4 recalls the (V-A) shape of the positron spectrum in μ^+ decay, and Table 1 reproduces its dependence upon the usual parameters ρ, η, δ, and ξ. The forward-backward asymmetry (where "forward" is defined to be opposite to the μ^+ spin direction) is complete at the energy endpoint $x=1$, where the forward decay rate vanishes in the (V-A) limit. Note that all experiments sensitive to ξ actually measure the product ξP_μ, where P_μ is the polarization along its direction of motion of a μ^+ which arises from π^+ decay at rest. According to (V-A), and/or if there exists only one muon-neutrino and it is massless, $P_\mu \equiv -1$. Measurement of this product can enhance the sensitivity of such experiments to departure from (V-A).

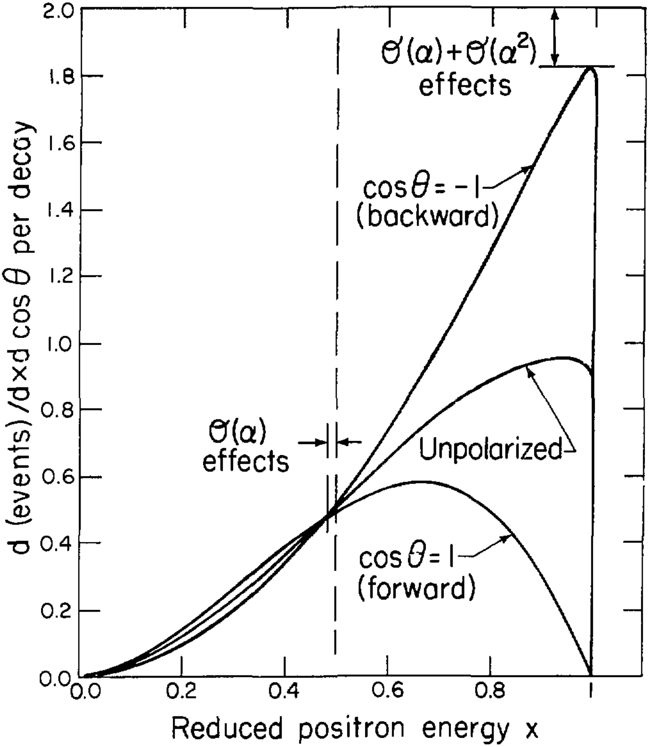

Fig. 4. Distribution in $x=E_{e^+}/E_{e^+}(\text{max})$ for μ^+ decay, according to (V-A). The parameter is $\cos\theta$, where θ is the angle between the forward direction (opposite to the μ^+ spin direction) and the positron momentum. In the forward direction near x=1, the lowest curve approaches (1-4x) before radiative corrections are applied. The curves are radiatively corrected to order α (α^2 near the endpoint), and take into account the finite positron mass. The decay parameters ρ, δ, η, and ξ parameterize, respectively, the shape of the unpolarized-μ curve, the shape of the difference between polarized-μ curves, the low-energy shape of the unpolarized-μ curve, and the magnitude of the difference between polarized-μ curves.

Table 1. Definition and "classical" measurements of the muon-decay parameters. The defining equation sums over final-state helicities and is written to lowest order in m_e/m_μ and α.

$$\frac{d\Gamma^{+}}{x^2 dx d\cos\theta} \propto (3-2x)+(\frac{4}{3}\rho-1)(4x-3)+12\frac{m_e}{x m_\mu}(1-x)\eta$$

$$+\left[(2x-1)+(\frac{4}{3}\delta-1)(4x-3)\right]\xi P_\mu \cos\theta$$

Parameter	World average	Primary experiment(s)
"symmetric shape"	$\rho=0.7518\pm0.0026$	Bardon et al. (Ref. 7) Peoples et al. (Ref. 8)
"low energy"	$\eta=-0.12\pm0.21$	Derenzo (Ref. 9)
"asymmetric shape"	$\delta=0.755\pm0.009$	Fryberger (Ref. 10)
"polarization"	$\xi P_\mu=0.972\pm0.013$	Akhmanov et al. (Ref. 11)

Table 1 recounts the experimental successes [7,8,9,10,11] of the 1960's (see Ref. 12 for a complete review). Consistency with the (V-A) predictions was achieved, save for a 2.2-standard-deviation discrepancy in ξ. The symmetric and asymmetric shape parameters ρ and δ were extremely well-measured; one wonders if modern technology can produce a large further reduction in the systematic uncertainties. The error on the low-energy parameter η can be improved with higher statistics and positron energy resolution. To keep abreast of new η measurements, however, the radiative corrections should eventually be carried to second order. The classical measurement of ξ, performed in emulsion at 140 kGauss, did not have access to precise positron energy information. The result was based on the *mean energy-independent front-back asymmetry*. The fact that the rate near $x=1$ is nearly proportional to $(1-\xi)$ in the forward direction should make possible a considerably more precise result in a future experiment.

B. New Measurements of Decay Positron Polarization at SIN

Preliminary results from the ETH/Zurich-SIN-Mainz group were reported at the 8th ICOHEPANS (Vancouver '79)[2]. The experiment analyzes the polarization of positrons from μ^+ decay by detecting their annihilation and Bhabha scattering in a magnetized Fe foil. Both the longitudinal and transverse e^+ polarization are analyzed; the latter is measured both within and normal to the plane formed by the e^+ momentum and μ^+ spin. This is made possible by precession of the μ^+ spin in a plane parallel to the foil (Fig. 5).

The preliminary results of this experiment are summarized in Table 2. The longitudinal e+ polarization is

$$P_L^e=0.94\pm0.08.$$

This is a substantial improvement upon the world average, but not a strong constraint on theory, compared for example to the 1.3% error on ξP_μ (Table 1). The transverse e^+ polarization is a function of the parameters α, α', β, and β', which, like the aforementioned muon decay parameters, depend on the scalar, pseuduscalar, vector, axial vector, and/or tensor coefficients in, for example, the charge-retention Hamiltonian (see Ref. 13 for full details). The primed parameters are T violating, corresponding to e^+ polarization out of the $\vec{p}_e$-$\vec{\sigma}_\mu$ plane. Under various conditions of physical interest, $\alpha=\alpha'=0$. If so, the experiment yields

$$\beta/A=-0.004\pm0.033$$
$$\beta'/A=-0.003\pm0.033,$$

where A is a sum of squares of coefficients approximately equal to 16.

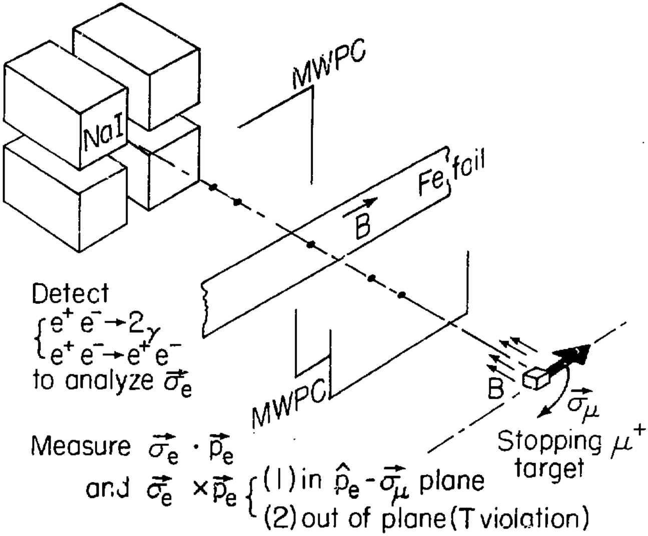

Fig. 5. Apparatus of Corriveau <u>et al</u>. (ETH/Zurich-SIN-Mainz collaboration, Ref. 2). The experiment measures the longitudinal and transverse polarization of μ^+-decay positrons. Both interesting types of particle pairs produced in the magnetic foil (2γ or e^+e^-) are detected; the magnetization is reversed at 15-minute intervals. Plastic scintillators (not shown) and 3 multiwire proportional chambers record the charged particle trajectories; energies of e^+, e^-, and γ are measured in four NaI crystals. The plane formed by the positron momentum and the muon spin rotates continuously as the latter precesses in the magnetic field near the stopping target. Transverse polarization both within and perpendicular to this plane is analyzed.

Table 2. Preliminary results of Corriveau *et al.* (ETH/Zurich-SIN-Mainz collaboration, Ref. 2), on the longitudinal polarization P_L^e and transverse polarization $\vec{P}_T^e$ of positrons from polarized μ^+ decay. Components of transverse polarization both within and perpendicular to the muon spin-positron momentum plane are measured. The notation is that of Scheck (Ref. 13).

Result for longitudinal polarization:

$$P_L^e = 0.94 \pm 0.08$$

$$[P_L^e \text{ (previous world average)} = 1.00 \pm 0.14]$$

$\vec{P}_T^e = \vec{P}_T^e(x, \alpha, \alpha', \beta, \beta')$, where

$$x \equiv \text{reduced positron energy}$$

$$\alpha \equiv |C_S|^2 + |C_S'|^2 - |C_P|^2 - |C_P'|^2$$

$$\beta \equiv |C_V|^2 + |C_V'|^2 - |C_A|^2 - |C_A'|^2$$

$$\left.\begin{aligned} \alpha' &\equiv 2\,\mathrm{Im}(C_S C_P'^{*} + C_S' C_P^{*}) \\ \beta' &\equiv 2\,\mathrm{Im}(C_V C_A'^{*} + C_V' C_A^{*}) \end{aligned}\right\} \text{T violating}$$

$$C_i \equiv \text{coefficient of } (\bar{e}\Gamma_i\mu)(\bar{\nu}_\mu\Gamma^i\nu_e)$$

$$C_i' \equiv \text{coefficient of } (\bar{e}\Gamma_i\mu)(\bar{\nu}_\mu\Gamma^i\gamma_5\nu_e)$$

in charge-retention Hamiltonian.

Results for α, α', β, β' free:

$\beta/A = -0.057 \pm 0.057$ $\qquad$ $\alpha/A = 0.16 \pm 0.12$

$\beta'/A = -0.049 \pm 0.057$ $\qquad$ $\alpha'/A = 0.14 \pm 0.14$,

where $A \approx 16$.

Results for $\alpha \equiv \alpha' \equiv 0$, β and β' free:

$\beta/A = -0.004 \pm 0.033$

$\beta'/A = -0.003 \pm 0.033$

In the same notation, the muon decay parameter η is

$$\eta=(\alpha-2\beta)/A.$$

The parameter α is zero if $|C_S|=|C_P|$ and $|C_S'|=|C_P'|$ in the charge-retention Hamiltonian (see Table 2 and Ref. 13). Alternatively, one may construct[14] a "phenomenological gauge-theory Lagrangian"

$$\mathcal{L}\propto\bar{e}\gamma^{\mu}(1-\gamma_5)\nu_e\bar{\nu}_{\mu}\gamma_{\mu}(1-\gamma_5)\mu+\delta\bar{e}\gamma^{\mu}(1+\gamma_5)\nu_e\bar{\nu}_{\mu}\gamma_{\mu}(1+\gamma_5)\mu+h\bar{e}\nu_e\bar{\nu}_{\mu}\mu+h'\bar{e}\gamma_5\nu_e\bar{\nu}_{\mu}\gamma_5\mu$$

allowing for an arbitrary combination of left, right, scalar, and pseudoscalar couplings, e.g. exchange of W_L and W_R (without mixing), plus charged Higgs. In this construction, again, $\alpha=0$[14]. Therefore, in these interesting cases,

$$\eta=-2\beta/A,$$

and the SIN result may be interepreted as

$$\eta_{\alpha=0}=0.008\pm0.066.$$

This is an important advance over the world average

$$\eta=-0.12\pm0.21.$$

Possibly, the error would shrink further if T invariance were assumed.

C. New Experiments Measuring Muon-Decay Parameters

Three new experiments of which I am aware are listed in Table 3. (Apologies are extended to those pursuing other initiatives, or whose institutional affiliations are incorrectly reproduced). I have already mentioned the large commitment being devoted to the Time Projection Chamber at Los Alamos[15]. It is expected to record $\gtrsim 10^8$ decay positrons from positive muons stopped in the methane TPC gas, with good momentum analysis over 4π solid angle except along (or opposite to) the (axial) direction of muon polarization. Muon depolarization (due both to epithermal and to thermal muonium formation in the methane) is expected to occur at the 1-2% level within the magnetic field. The *statistical* errors on all four muon decay parameters are calculated to be $\approx$one order of magnitude smaller than existing combined uncertainties (Table 3). For discussion of the expected *systematic* errors, the reader is referred to J.D. Bowman's presentation.

Experiment 134/176 (Berkeley-British Columbia) at TRIUMF[16] utilizes a classical short-focussing solenoid as a single-channel positron-momentum analyzer. Despite the concomitant sacrifice in event rate it is quite useful for measurement of the low-energy parameter η, because the positrons encounter only vacuum between the μ^+-stopping scintillator and the annular momentum slit at the focal

Table 3. Experiments in progress which measure the muon-decay parameters. Anticipated <u>statistical</u> errors are shown in parentheses; anticipated <u>overall</u> errors are shown without parentheses.

	σ (overall) (σ(statistical))			
	ρ	η	ξP_μ	δ
World average (Ref. 12)	0.0026	0.21 0.066[a]	0.012	0.009
LASL #455 (Ref. 15) LASL/Chicago/NRC/Carleton (Anderson/Bowman)	(0.00023)	(0.006[b])	(0.001)	(0.006)
TRIUMF #134/176 (Ref. 16) Berkeley/British Columbia I (Crowe)		(<0.1)	≤0.005 (≈0.001)	
TRIUMF #185 (Ref. 17) Berkeley/British Columbia II			≈0.001 (≈0.0003)	

[a] from measurement by Corriveau <u>et al</u>. (Ref. 2) of decay positron transverse polarization, assuming α=0 (see Table 2).

[b] calculated statistical error does not include effects of radiative corrections.

plane. The spectrometer is to be adapted for use in measuring ξP_μ by precessing the μ^+ spin in a plane containing the solenoid axis. It will operate in a manner similar to that of a standard "muon spin rotation" apparatus, with the ability to select a positron momentum band corresponding to nearly complete time-modulation of the observed decay rate. This technique must sacrifice the advantage of a longitudinal magnetic field to "hold" the spin; muon depolarization is to be suppressed by chemical means.

Experiment 185 at TRIUMF[17], under construction by a second Berkeley-British Columbia group, is aimed at a definitive measurement of ξP_μ (statistical and systematic error $\lesssim 0.1\%$). Most of the running will be devoted to precise (0.5%) momentum measurement of decay positrons emitted opposite to the stopped muon spin direction, where (V-A) predicts that the rate must vanish. Only $\approx 2\times10^5$ events, obtainable in a few shifts, can provide the necessary statistical precision. The data sample thus should be highly complementary to that which will be collected by the Time Projection Chamber.

The group designing Experiment 185 feel it necessary to insure that uncertainties in correcting for muon depolarization, both in the beam transport and in the stopping medium, can be demonstrated *a priori* to be negligible at the 10^{-3} level. The experiment requires use of a "surface" μ^+ beam derived from decay of π^+ resting within a few mg/cm^2 of the surface of a thin carbon target illuminated by 520 MeV protons from TRIUMF. Each muon is to be tagged in position and angle by low-mass driftchambers, and in phase with respect to cyclotron RF (43 nsec period) to suppress contamination by "cloud" muons born promptly near the target. At TRIUMF, design and operation of such beams is highly developed[18]. Depolarization in the liquid He stopping target is to be suppressed by the uniquely high ionization potential of He: only $\lesssim 2\%$ of the thermalized muons will be bound in muonium. Depolarization of muons in this fraction will be suppressed by $\gtrsim\times 50$ in the longitudinal magnetic field. Table 4 lists the expected sources and levels of depolarization uncertainty in the beam and in the stopping target.

I shall take the opportunity to exhibit two sketches of the spectrometer being constructed. Figure 6 is a layout of the experiment, showing the upstream target solenoid and downstream 90° focussing positron spectrometer. Figure 7 exhibits the target solenoid (length 1 m) and nearby detectors in greater detail. The scale of the experiment is such that operation may be expected by early 1982.

III. REMARK ON CHARGED HIGGS LIMITS FROM μ DECAY

Up to this point I have not related the discussion of muon-decay parameters to any physical mechanism for departure from (V-A) predictions. The remainder of this review deals with two such mechanisms: charged Higgs exchange, and right-handed gauge boson (W_R) exchange (section IV).

Table 4. Anticipated depolarization of surface-beam muons in TRIUMF Experiment 185 (Ref. 17)

Depolarization of Beam

Source	Upper limit on error in correction
Coulomb scattering upstream of target	0.0005
Beam divergence at target	0.0006
Cloud muon contamination	0.0002
Jaw/slit scattering	?

Depolarization in Liquid He Target ($\vec{B} \simeq 7$ kGauss)

Source	Upper limit on correction to polarization
Coulomb scattering	0.00001
Epithermal muonium formation	0.00001
Thermal muonium formation	0.00050
Impurities	0.00010
Wall stops	0.00010
Molecular ion rotation	0.00005
Total	0.00080

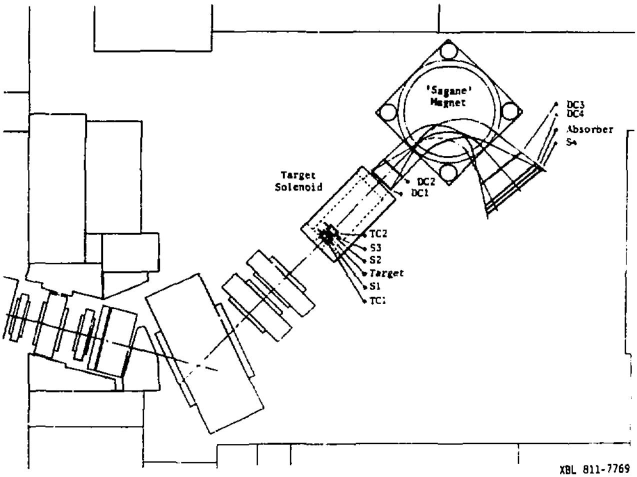

Fig. 6. Apparatus under construction for the Berkeley-British Columbia Experiment #185 at TRIUMF (Ref. 17). The experiment will be sensitive to the product of ξ, the polarization parameter describing μ^+ decay, and the polarization P_μ of the μ^+ from π^+ decay at rest. The anticipated sensitivity $\sigma(\xi P_\mu) \approx 10^{-3}$ would represent a factor 13 improvement over the current world average. It is to be achieved by measuring at the high-energy endpoint the rate of decay e^+ emission opposite to the μ^+ polarization direction. If this rate is found to be zero with the anticipated sensitivity, the mass of any right-handed gauge boson W_R must exceed 600 GeV/c^2. Two magnets are used in the apparatus: the target solenoid's axial field "holds" the stopped μ^+ spin and focusses the forward decay e^+, and the "Sagane" cylindrical dipole magnet is used in a 90° spectrometer with driftchambers DC2 and DC3 at the foci.

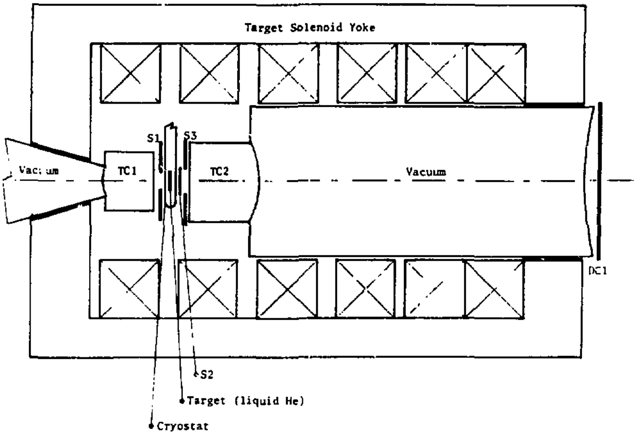

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Fig. 7. Enlarged view of apparatus in the vicinity of the target, now being constructed for the Berkeley-British Columbia Experiment #185 at TRIUMF (Ref. 17). (The full layout is shown in Fig. 6). The experiment will exploit the uniquely high ionization potential of (liquid) He in order to suppress depolarization due to muonium formation by stopping μ^+. Depolarization in the small residual muonium fraction will be made negligible by the Paschen-Back effect in the ≥ 7 kGauss longitudinal "holding" field. In the figure, TC1, TC2, and DC1 are low-mass driftchambers; S1-S3 are scintillators.

Haber, Kane et al.[19], and McWilliams and Li[20], have introduced a general charged-Higgs coupling which contributes to the Lagrangian a piece

$$\mathcal{L}^{C.H.}=2^{3/4}[G_F^{\frac{1}{2}}M_{H^+}](\bar{\psi}_f[\alpha^R_{ff'}\tfrac{1}{2}(1+\gamma_5)+\alpha^L_{ff'}\tfrac{1}{2}(1-\gamma_5)]\psi_{f'}\bar{H}(x)+h.c.),$$

where f' and f are the initial and final fermions, and M_{H^+} is the charged Higgs mass. I have used the notation of Ref. 20; in the notation of Ref. 19,

$$\beta_{Kane}=2^{\frac{1}{2}}M_\ell/(M_{H^+}\alpha^L_{\ell\nu}),$$

where ℓ is a charged lepton and ν is its neutrino. With a coupling of this form, $\alpha=0$ (see section II.B), and $\eta=-2\beta/A$; the SIN positron polarization experiment [2] constrains $\alpha_{ff'}$ just as does η:

$$(\text{SIN } \vec{\sigma}_e\times\vec{p}_e) \qquad -0.20<\alpha^L_{\mu\nu}\alpha^L_{e\nu}<0.24. \qquad \text{(III-1)}$$

By comparison, the existing measurement of ξ constrains

$$(\xi) \qquad |\alpha^L_{\mu\nu}|\{(\alpha^L_{e\nu})^2+(\alpha^R_{e\nu})^2\}^{\frac{1}{2}}<0.33. \qquad \text{(III-2)}$$

If a future experiment measures $\eta=0\pm0.016$, or $\xi=1\pm0.001$, the magnitude of the numbers in (III-1) and (III-2) will be reduced to 0.063.

Lest optimism be encouraged by this prospect, let me repeat a point emphasized by the authors of Refs. 19 and 20. The neutral (and by inference, the charged) Higgs mass is expected to be at least of order 3-10 GeV/c^2, and the coupling parameter $\alpha_{\ell\nu}$ is expected to be of order m_ℓ/m_{H^+}. If so, these low-energy experiments are hopeless! If $\alpha_{\ell\nu}$ turns out not to be proportional to m_ℓ/m_{H^+}, measurement of the branching ratio $(\pi^+\to e^+\nu_e)/(\pi^+\to\mu^+\nu_\mu)$ can be expected, for typical experimental accuracy, to produce a 1-2 order-of-magnitude greater sensitivity to (some) $\alpha_{ff'}$ than can be expected from the μ decay experiments. Unless there exists a mechanism to suppress quark-Higgs relative to lepton-Higgs coupling, there remains little motivation to search for effects of charged Higgs exchange in muon decay.

IV. CONSTRAINTS ON THE EXISTENCE OF W_R

The possible existence of one or more right-handed gauge bosons would be of great consequence to selection of a gauge group for grand unification. Moreover, considerable aesthetic appeal is held out by the possible restoration of "manifest left-right symmetry" to the electroweak interaction above some mass scale. A general discussion of the phenomenological constraints on right-handed currents is available from Bég, Budny, Mohapatra, and Sirlin[21], as appended by Holstein and Treiman[22].

This discussion will be phrased in terms of the physical variables $\delta \equiv (M(W_L)/M(W_R))^2$, where $M(W_L)$ $[M(W_R)]$ is the mass of the left- [right-] handed gauge boson, and ζ, the angle by which W_L and W_R mix. This angle is the same as in Ref. 21. In the (V-A) limit, $\delta=\zeta\equiv 0$. Near this limit, the variables used in Refs. 21 and 22 are:

$$\text{(Ref. 21)} \begin{cases} \eta_{AV} \approx -1+2(\delta-\rho+4\delta\zeta-\delta^2) \\ \eta_{AA} \approx 1+4(\zeta+\zeta^2-2\delta\zeta) \end{cases}$$

$$\text{(Ref. 22)} \begin{cases} x \approx \delta-\zeta \\ y \approx \delta+\zeta \end{cases}$$

In these terms, the present experimental situation is summarized by the two-standard-deviation limits in Fig. 8. At present, the primary limit on the mixing angle ζ is set by the ρ parameter in μ decay; the primary limit on the mass-square ratio δ is set by the electron polarization in Gamow-Teller β decay[23]. Note that the scales of these contours are proportional to the square root of the corresponding experimental error. The elliptical contour in Fig. 8 arising from measurement of ξP_μ would have provided the most severe constraint on δ, if the central value had not fallen well below the (V-A) prediction. The remaining muon decay parameters retain their (V-A) values even if δ and ζ are nonzero[21].

Turning to future experimental constraints, Fig. 9 exhibits the effect of improvements envisaged by the Princeton group[24] upon their previous measurements[25] of the asymmetry parameter A(0) in ^{19}Ne β decay. Figure 10 shows limits which may be obtained by new measurements of ρ and ξ, as well as by comparison of electron helicity in Fermi and Gamow-Teller β decay. If the new experiments do remain relatively consistent, and if their relative sensitivities are distributed as Fig. 10 would suggest, most of the new information on possible right-handed currents will come from the measurement of ξP_μ. This helps to explain our enthusiasm at LBL and TRIUMF for undertaking so exacting a measurement.

I have appended in Fig. 11 and its caption the rate estimates for a conceivable future search for W_R effects in the reaction $e^- p \to \nu_e X$ in 30 GeV e^- $\times$800 GeV p collisions at the proposed HERA facility. It would be an enormously challenging experiment. The 500-GeV mass scale seems to go a long way toward equalizing in difficulty even so disparate a collection of experiments as Figs. 9-11 represent.

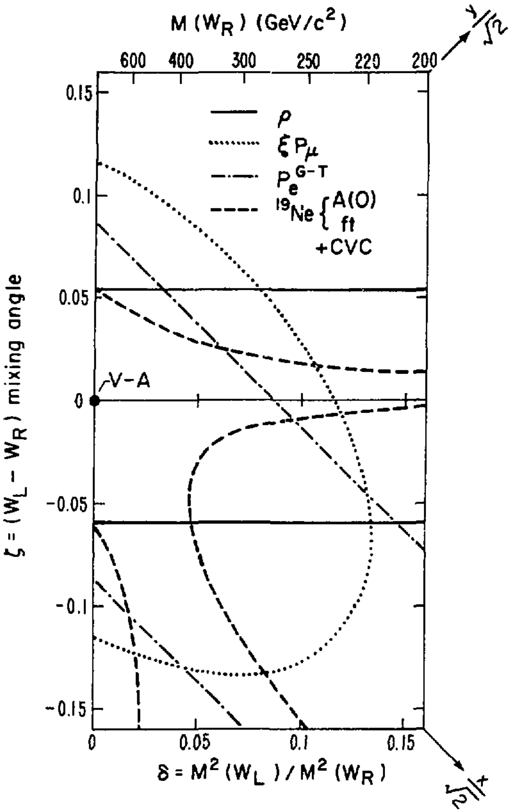

Fig. 8. Existing two-standard-deviation limits on the parameters δ (square of $M(W_L)/M(W_R)$ mass ratio) and ξ (W_L-W_R mixing angle) describing a possible right-handed gauge boson W_R. See Ref. 21 for the definition of ζ. If only a single left-handed gauge boson exists, $\delta=\zeta\equiv0$. The mixing angle is limited by the muon decay parameter ρ (Ref. 8); and also by the asymmetry parameter A(0) in ^{19}Ne β decay (Ref. 25), combined with decay rate measurement and calculations using the conserved-vector-current hypothesis (Ref. 22). The W_R mass is limited by the electron polarization measured in Gamow-Teller β decay (Ref. 23), and also by measurement of the product ξP_μ of the polarization parameter ξ describing muon decay and the polarization P_μ of a μ^+ from π^+ decay at rest.

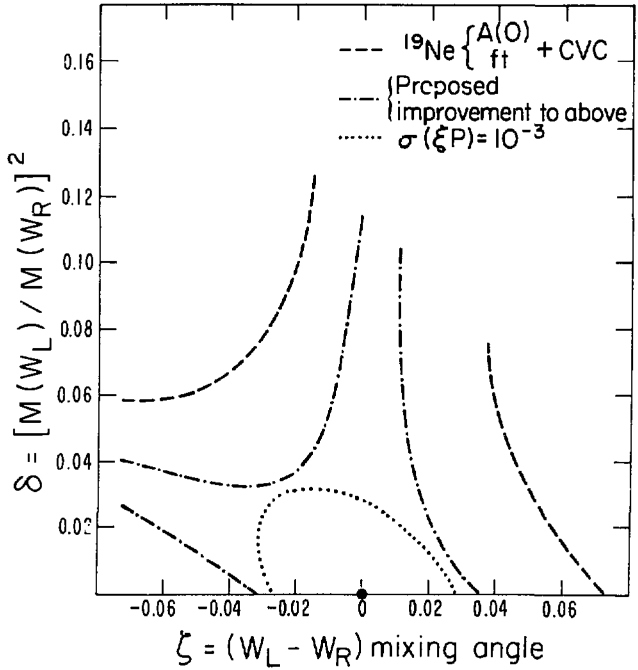

Fig. 9. Proposed improvement by the Princeton group (Ref. 24) upon the two-standard-deviation limits on ζ and δ based in part on their previous measurement of the asymmetry parameter A(0) in ^{19}Ne decay (Refs. 22, 25). The existing limit represented by the dashed line is the same as that in Fig. 8 (note reversal of axes). For comparison, the restriction on δ and ζ which would be obtained by a 0.1% measurement of ξP_μ (see Fig. 10) is given by the dotted ellipse.

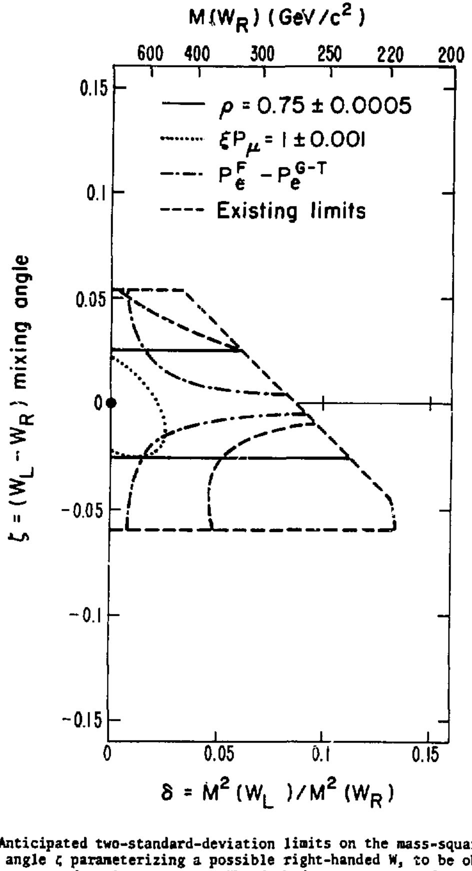

Fig. 10. Anticipated two-standard-deviation limits on the mass-squared ratio δ and mixing angle ζ parameterizing a possible right-handed W, to be obtained by experiments proposed or in progress. The dashed contours reproduce the most restrictive of the existing limits in Fig. 8. The error attached to the muon decay parameter ρ is twice the *statistical* error anticipated from 10^8 events in the Los Alamos-Chicago-NRC/Canada-Carleton experiment under construction at LAMPF. A comparison of electron polarization in Fermi and Gamow-Teller transitions proposed by the Michigan group (Ref. 26) will limit the product $\zeta\delta$ (dot-dashed contour). The dotted ellipse corresponds to the sensitivity anticipated for the Berkeley-British Columbia measurement of ξP_μ (Ref. 17; Figs. 6 and 7).

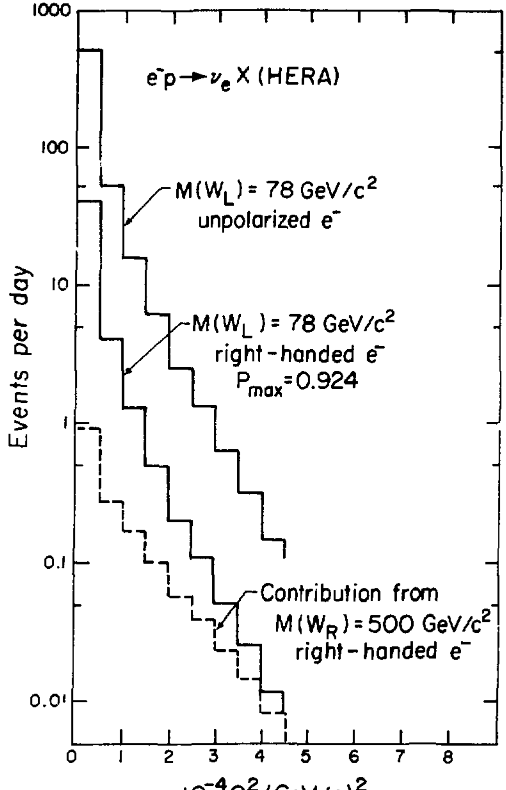

Fig. 11. Conceivable search for effects of a right-handed gauge boson W_R at a future e^-p colliding-beams facility. Rate estimates for HERA, at 30 GeV e^- ×800 GeV p the most ambitious of the proposed e^-p rings, are adapted from the ECFA workshop proceedings (Ref. 27). The top curve is the event rate per interval $\Delta(Q^2)=5000$ (GeV/c)^2 for the as-yet-unobserved reaction $e^-p \rightarrow \nu_e X$, assuming *unit* detection efficiency and *average* luminosity of 10^{32} cm^{-2} sec^{-1}. The contribution from W_R exchange ($M(W_R)=500$ GeV/c^2) is undetectable against this "background". The latter may be reduced by longitudinal electron polarization (0.924 is the quantum limit). *In this limit, for example, for $Q^2>10^4$ (GeV/c)^2 W_R exchange* makes a 15% difference in an event rate of 2 per day, using the ideal luminosity and detection efficiency mentioned above.

V. ACKNOWLEDGMENT

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REFERENCES

[1] A.R. Clark, K.J. Johnson, L.T. Kerth, S.C. Loken, T.W. Markiewicz, P.D. Meyers, W.H. Smith, M. Strovink, and W.A. Wenzel (Berkeley/LBL); R.P. Johnson, C. Moore, M. Mugge, and R.E. Shafer (Fermilab); G.D. Gollin, F.C. Shoemaker, and P. Surko (Princeton).

[2] F. Corriveau et al., submitted to 8th International Conference on High Energy Physics and Nuclear Structure, Vancouver, Canada, August 1979. See also J. Egger, in the Proceedings of the above Conference, edited by D.F. Measday and A.W. Thomas, Nucl. Phys. A335, 91-94 (1980).

[3] A.R. Clark et al., Phys. Rev. Lett. 46, 299 (1981).

[4] C.Y. Prescott et al., Phys. Lett. 77B, 347 (1978), and Phys. Lett. 84B, 524 (1979).

[5] F. Wilczek and A. Zee, Nucl. Phys. B106, 461 (1976); T. Cheng and L. Li, Phys. Rev. D16, 1425 (1977); D. McKay and H. Muczek, Phys. Rev. D19, 985 (1979); M. Abud and A. Bottino, Nuovo Cimento 51A, 473 (1979); Z. Hioke, Prog. Theo. Phys. 58, 1859 (1977).

[6] S. Weinberg and B.W. Lee, Phys. Rev. Lett. 38, 1237 (1977); Y. Achiman and B. Stech, Phys. Lett. 77B, 384 (1978). These models and those of Ref. 5 specify μ^+-$\bar{M}^0$ couplings of Fermi strength with $m_{M^0} \approx 4$-5 GeV/c^2 and $B(\bar{M}^0 \to \mu^+\mu^-\nu) \approx 0.1$-$0.2$.

[7] M. Bardon et al., Phys. Rev. Lett. 14, 449 (1965).

[8] J. Peoples, Ph.D. Thesis, Columbia University, Nevis Cyclotron Laboratory Report No. 147 (1966).

[9] S. Derenzo, Phys. Rev. 181, 1854 (1969).

[10] D. Fryberger, Phys. Rev. 166, 1379 (1968).

[11] V.V. Akhmanov et al., Sov. J. Nucl. Phys. 6, 230 (1968).

[12] A.M. Sachs and A. Sirlin, in Muon Physics, edited by V.W. Hughes and C.S. Wu (Academic Press, New York, 1975), Vol. II, pp. 49-81.

[13] F. Scheck, Physics Reports 44, 187 (1978). See also Ref. 12.

[14] C.J. Martoff, "Reconsideration of a General Amplitude for Muon Decay from a Gauge-Theory Style Lagrangian", University of California, Berkeley report, 1978 (unpublished); C.J. Martoff, private communication.

[15] H.L. Anderson, J.D. Bowman, C.M. Hoffman, H.S. Matis, R.J. McKee, D.E. Nagle, W.W. Kinnison, C.K. Hargrove, H. Mes, A.L. Carter, and D. Kessler, "High Precision Study of the μ^+ Decay Spectrum" (H.L. Anderson and J.D. Bowman, spokesmen), Proposal #455 to the Los Alamos Meson Physics Facility, November 1978 (unpublished); R.J. McKee, "Extraction of the Michel Parameters by Maximum Likelihood", LAMPF Experiment #455 internal report, 1980 (unpublished); J.D. Bowman, these Proceedings.

[16] J.H. Brewer, C.M. Clawson, K.M. Crowe, C.J. Martoff, J.M. Miller, and W.A. Zajc, "Measurement of the Eta Parameter in Muon Decay" (K.M. Crowe, spokesman), Proposal #134 to TRIUMF, 1979 (unpublished); J.H. Brewer, C.M. Clawson, K.M. Crowe, J.A. Jansen, C.J. Oram, and M. Salomon, "Measurement of the Parameter ξ in the Muon Decay" (K.M. Crowe, spokesman), Proposal #176 to TRIUMF, 1980 (unpublished).

[17] G. Gidal, C. Oram, H.M. Steiner, M. Strovink, and R.D. Tripp, "Precise Measurement of the Polarization Parameter ξ: A Search for the Effects of a Right-handed Gauge Boson in μ^+ Decay", Proposal #185 to TRIUMF, 1980 (unpublished).

[18] C.J. Oram, J.B. Warren, G.M. Marshall, and J. Doornbos, Nucl. Inst. and Meth. 179, 95 (1981).

[19] H.E. Haber, G.L. Kane, and T. Sterling, Nucl. Phys. B161, 493 (1979).

[20] B. McWilliams and L.-F. Li, Carnegie-Mellon University preprint COO-3066-146 (April, 1980).

[21] M.A.B. Bég et al., Phys. Rev. Lett. 38, 1252 (1977).

[22] B.R. Holstein and S.B. Treiman, Phys. Rev. D16, 2369 (1977).

[23] J. Van Klinken, Nucl. Phys. 75, 145 (1966).

[24] D. Schreiber and F.P. Calaprice, "Beta Asymmetry ($A\vec{J}\cdot\vec{p}_e$) of ^{19}Ne and Its Relationship to SCC - CVC and Right-handed Currents", Princeton University research proposal, 1980 (unpublished); F.P. Calaprice, private communication.

[25] F.P. Calaprice et al., Phys. Rev. Lett. 35, 1566 (1975).

[26] D. Newman and A. Rich, "Precision Positron Polarimetry - A New Technique in Weak Interaction Studies", University of Michigan

Technical Report DE-AC02-79ER10451, 1980 (unpublished); A. Rich, private communication.

[27] Study on the Proton-Electron Storage Ring Project HERA (Report of the Electron Proton Working Group of ECFA), edited by U. Amaldi, Report No. ECFA 80/42 - DESY HERA 80/01, 17 March 1980, Section II.2, Fig. 2.4 (unpublished).

DISCUSSION

Ling-Lie Wang, Brookhaven National Laboratory - I just want to comment on your first point. Mark J at PETRA has set a very stringent limit on the existence of heavy leptons, I think with larger mass than you have. It's just another source of experimental input.

Strovink - Not on neutral leptons.

Wang - Their limits are on charged leptons.