EXPERIMENT E614 AT TRIUMF:
A CLOSE LOOK AT MUON DECAY

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Muon decay, a process which involves only the weak interaction, is precisely described within the Standard Model. Therefore, a precision measurement of the decay distribution will provide an unambiguous test of physics beyond the Standard Model. Experiment E614, an experiment under preparation at TRIUMF, will determine the energy and angular distributions of positrons from μ^+ decay to a precision of one part in 10^4. After discussing the general framework for muon decay, the experiment and its sensitivity to new physics are described.

1 Muon Decay - Formalism and Motivation

A general expression for the muon decay distribution can be written in terms of the weak interaction couplings. In the case of the Standard Model, only the vector coupling of left-handed to left-handed leptons is allowed. A more general expression, including scalar, vector, and tensor interactions can be written as

$$\frac{d^2\Gamma}{dx\ d(cos\theta)} = |\sum_{\substack{i=left,right\\ j=left,right\\ \gamma=Tensor,Vector,Scaler}} g^{\gamma}_{ij} < \overline{\psi_{e_i}}|\Gamma^{\gamma}|\psi_{\nu_e} >< \overline{\psi_{\nu_\mu}}|\Gamma_{\gamma}|\psi_{\mu_j} > |^2 \ , \tag{1}$$

where the chiralities of the neutrinos are determined by selection rules on i, j, and γ. This expression allows for couplings of arbitrary combinations of left-handed and right-handed leptons. This expression can be greatly simplified by defining the Michel parameters[1] in terms of the coupling constants. The Michel parameters ρ, δ, ξ, and η are defined as follows:

$$\rho = \frac{3}{4} - \frac{3}{4}[\ |g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + Re(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR})\ ]\ , \tag{2}$$

$$\xi\delta = \frac{3}{4} - \frac{3}{4}[|g^V_{LR}|^2 + |g^V_{RL}|^2 + 4|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + 2|g^V_{RR}|^2 + \frac{1}{2}|g^S_{RR}|^2 + \frac{1}{2}|g^S_{LR}|^2 + Re(g^S_{RL}g^{T*}_{RL} - g^S_{LR}g^{T*}_{LR})\ ]\ , \tag{3}$$

$$\xi = 1 - [\frac{1}{2}|g^S_{RR}|^2 + \frac{1}{2}|g^S_{LR}|^2 + 2|g^V_{RR}|^2 + 4|g^V_{RL}|^2 - 2|g^V_{LR}|^2 - 2|g^T_{LR}|^2 + 8|g^T_{RL}|^2 + 4Re(g^S_{RL}g^{T*}_{RL} - g^S_{LR}g^{T*}_{LR})\ ]\ , \tag{4}$$

$$\eta = \frac{1}{2}Re[\ g^V_{LL}g^{S*}_{RR} + g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL}) + g^V_{RR}g^{S*}_{LL}\ ]\ . \tag{5}$$

The notation is that of Fetscher and Gerber.[2] The subscripts RL refer to the coupling of a right-handed electron current to a left-handed muon current, LR to the coupling of a left-handed electron current to a right-handed muon current, and so on. In the limit where the electron mass and radiative corrections are neglected, the differential distribution for positrons from μ^+ decay may then be written in terms of these parameters,

$$\frac{d^2\Gamma}{x^2dx\ d(cos\theta)} \propto 3(1-x) + \frac{2}{3}\rho(4x-3) \pm P_\mu\xi\cos\theta[(1-x) + \frac{2}{3}\delta(4x-3)]\ , \tag{6}$$

	Standard Model	Current Limits	E614(A)	(B)	(C)	(D)
$\lvert g^S_{RR}\rvert$	0	<0.066	—	—	0.034	0.045
$\lvert g^V_{RR}\rvert$	0	<0.033	0.012	0.017	0.017	0.022
$\lvert g^T_{RR}\rvert$	0	$\equiv 0$				
$\lvert g^S_{LR}\rvert$	0	<0.125	—	—	0.034	0.046
$\lvert g^V_{LR}\rvert$	0	<0.060	0.012	0.015	0.015	0.018
$\lvert g^T_{LR}\rvert$	0	<0.036	—	0.010	—	0.013
$\lvert g^S_{RL}\rvert$	0	<0.424	—	—	—	—
$\lvert g^V_{RL}\rvert$	0	<0.110	0.012	0.012	0.012	—
$\lvert g^T_{RL}\rvert$	0	<0.122	—	0.008	—	—
$\lvert g^S_{LL}\rvert$	0	<0.55	—	—	—	—
$\lvert g^V_{LL}\rvert$	1	>0.96	>0.99977	>0.99942	—	—
$\lvert g^T_{LL}\rvert$	0	$\equiv 0$				

Table 1: Standard Model values and experimental upper limits (90% CL) for weak coupling constants with current limits taken from Fetscher and Gerber. Improved limits set by E614 based on our measurements of ρ, ξ, and δ assume: (A) V, A couplings only, (B) V, A and T couplings, (C) V, A and S couplings or (D) most general (V, A, S, and T) derivative-free couplings. For case (C), our measurement of η will also set a more stringent limit than above on the real (CP-conserving) part of g^S_{RR}.

where θ is the angle between the muon polarization and the outgoing positron direction, $x = E_e/E_{max}$, and P_μ is the muon polarization. A fourth Michel parameter, η, contributes to the energy spectrum when the electron mass is included in the analysis.[†]

In the Standard Model, only g^V_{LL} is non-zero. This is because the other couplings have been set to zero by fiat. In fact, the experimental case for setting these couplings to zero is not strong, as shown in Table 1.

The measured values for the Michel parameters[2] are shown in Table 2 along with their Standard Model values. Measurements to date support the

[†]In the actual experiment, the data will be compared with a decay distribution which includes the effects of radiative corrections and finite electron mass.

	Current Experimental Value	Standard Model Value
ρ	0.7518 ± 0.0026	$\frac{3}{4}$
δ	$0.7486 \pm 0.0026 \pm 0.0028$	$\frac{3}{4}$
$P_\mu \xi$	$1.0027 \pm 0.0079 \pm 0.0030$	1
η	-0.007 ± 0.0013	0

Table 2: The accepted values of the Michel parameters,[2] along with the Standard Model values.

Standard Model to within the quoted uncertainties.

The decay distribution predicted by the Standard Model - as given by equation 6 - is shown graphically in Figure 1. Deviations from the Standard Model values for the Michel parameters would be manifest in deviations from this decay distribution.

The goal of E614 at TRIUMF is to determine $d^2\Gamma/dx\ dcos(\theta)$ with improved precision, allowing the determination of the Michel parameters ρ, δ, and ξ to within a few parts in 10^4 (η will also be determined, but with a precision of roughly a part in 10^3). This will test for physics beyond the Standard Model. For example, these extra couplings may give evidence for weak gauge bosons which have not been included in the Standard Model.

2 The Experiment

E614 at TRIUMF will be the first experiment in which the Michel parameters will be extracted from a simultaneous measurement of the entire muon decay distribution. This will be accomplished by stopping polarized μ^+ at the center of a highly symmetric detector, sitting in a nearly uniform 2T solenoidal magnetic field. Data will be taken at a high rate, allowing the study of 10^9 μ^+ decays in approximately two weeks.

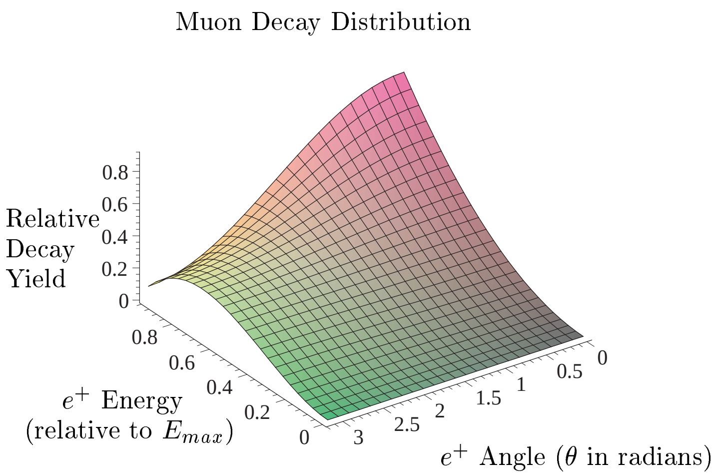

Figure 1: The distribution of e^+ from μ^+ decay as given by equation 6 .

2.1 The μ^+ Beam

The muons will be selected from a sample of pions decaying at rest, in which case the muons have a well defined helicity within the Standard Model. Beamline M13 [3] at TRIUMF will be used to select muons which originate from pions which stop very near the surface (within roughly 15 microns of the surface for a channel resolution $\frac{\Delta p}{p} \approx \frac{1}{2}\%$) of the pion production target. In this case, the muons lose little momentum in emerging from the target. Similarly, these "surface muons" undergo limited multiple scattering, and consequently lose very little polarization. The selected muons are expected to have a polarization of 0.9999.

The beam at TRIUMF is pulsed with a period of 43 ns. Most of the beam-related background is correlated in time with this accelerator time structure. The surface muons, however, are delayed in time by the π decay distribution (mean lifetime of 26 ns). A timing gate is used to select surface muons while discriminating against much of the beam-related background. The relatively long period of the TRIUMF beam is ideal for this experiment.

2.2 The Spectrometer

The spectrometer is required to obtain a precise measurement of the energy and angle of the decay positron. This is challenging, in part due to the limited energy (4.1 MeV), and consequently the limited range ($\approx$ 1 mm in CH_2), of

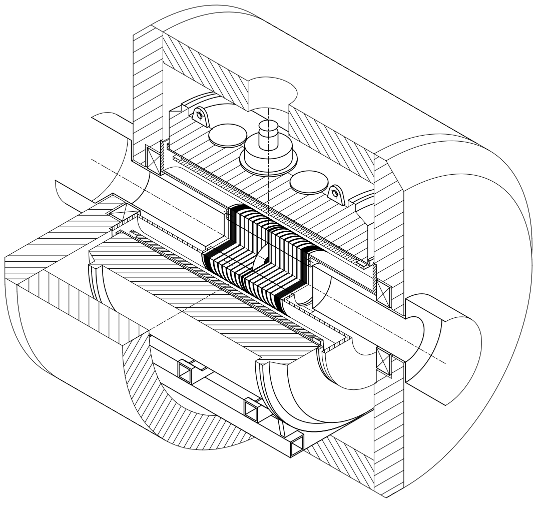

Figure 2: The E614 Spectrometer. The precision circular planar wire chambers with an active area ~ 40 cm in diameter are shown at the center of the 2T superconducting solenoid. The scale of the drawing is set by the bore of the solenoid, which is ~ 1m in diameter. Surrounding the magnet is an early concept drawing for the return yoke.

the incident muons. This constrains the amount of wire chamber and trigger material that can be placed in the path of the incoming muons but which are required for the tracking of the positrons.

The spectrometer, shown in Figure 2, is highly symmetric. The wire positions must be accurately determined in three dimensions. The wire positions with respect to the two coordinates transverse to the beam can be accurately verified by fitting straight tracks in the absence of a magnetic field. The coordinate along the beam is difficult to verify. For this reason, precise assembly techniques involving optical interferometry are used to verify the position of the wire planes in the dimension along the beam.

3 Sensitivity to new physics

The goal of the experiment is to test the values of the Michel parameters for consistency with the Standard Model at a level of 1 part in 10^4. For example, the present limits on δ are approximately 50 parts in 10^4 and are shown in Figure 3 as the extreme curves on either side of the central curve corresponding to the Standard Model value. The E614 sensitivity to variations in δ would lie within the width of the central line. Therefore, if E614 were to measure a

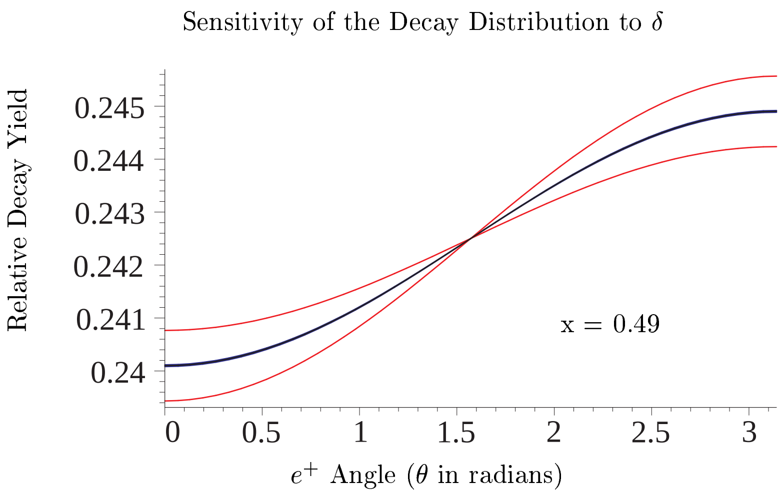

Figure 3: Dependance of the decay yield upon δ. The outer bands indicate the uncertainty in the decay yield due to the current experimental limits on δ (see equation 6 and Table 2). The distribution given by the Standard Model is at the center of this band, bounded by the sensitivity of E614. These limits are narrow enough to be difficult to discern on this plot, so that the three curves merge into a thick band. The distribution is evaluated at x = 0.49.

distribution falling between the existing limits and the E614 sensitivity, this would be indicative of a failure of the Standard Model. There is no evidence either for or against such a signal at this time.

More fundamentally, the experiment will provide constraints on possible non-zero values for weak couplings other than g^V_{LL}. In this case, the sensitivity to new physics is somewhat model dependent since specific models - such as models exhibiting manifest symmetry between the left-handed and right-handed CKM matrices - are chosen to reduce the number of free parameters. Expected limits on the coupling constants under various assumptions are given in Table 1.

To obtain new upper limits on the couplings implied by the precision in the Michel parameters expected from E614, the magnitudes of eight coupling constants were varied independently from zero up to the current limit for each coupling, and the two relative phases between tensor and scalar couplings were varied from 0 to π. For each combination of couplings and phases which satisfied the constraints imposed by the sensitivity of E614, maximum values of the couplings were saved. These values are shown in column D of Table 1. The second column shows the current limits as quoted in reference 2.

In the most general case D), limits on all of the RR and LR couplings are improved over current values but the RL and LL limits are unchanged. However, since very few extensions of the standard model include both scalar and tensor couplings, three additional cases were studied: A) only vector and axial vector couplings are allowed, B) all but scalar couplings are allowed, and C) all but tensor couplings are allowed. In all three cases, the analysis is greatly simplified because there are fewer couplings to vary and because the interference terms between scalar and tensor couplings in ρ, ξ, and δ disappear, allowing one to take advantage of the positive-definite nature of many of the terms.

Case A is a minimal extension of the standard model, in which only three independent vector coupling constants are needed. In this case the limit on the total deviation from V-A is quite stringent, as seen by the deduced lower limit on g^V_{LL}. This leads to significant new limits on the existence of right-handed currents in left-right symmetric theories.

Assuming that the right-handed neutrinos are light, non-zero g^V_{RR} is dependent upon the mass of the right-handed vector boson W_R, while non-zero g^V_{RL} and g^V_{LR} indicate mixing between the intermediate vector bosons W_L and W_R. A measurement of the parameters ξ and ρ will therefore set limits on both the left-right mixing angle ζ and the right-handed boson mass M_R. E614 will actually measure the quantity $P_\mu\xi$, and not ξ and P_μ separately. The value of P_μ depends on assumptions regarding the structure of the right-handed CKM matrix in left-right symmetric theories. Therefore, to be conservative one may take the limit for ξ to be the measured limit for $P_\mu\xi$. In that case ξ and ρ define contours in mixing angle - mass space given by Herczeg[4]:

$$\frac{1-\xi}{2} = \zeta^2 + \frac{M_L^4}{M_R^4} , \tag{7}$$

$$\rho = \frac{3}{4}(1-2\zeta^2) . \tag{8}$$

These two expressions assume that $g_R = g_L$. More general expressions that remove this assumption may be found in Herczeg.[4] Note that left-right symmetric theories require $g_R > 0.55 g_L$ to be consistent with existing experimental results.[5]

The experimentally allowed region at 95% CL is shown in Figure 4 under the assumption that the left- and right-handed CKM matrices are similar, indicating that E614 is sensitive to new particles with masses up to 819 GeV/c^2 and W_L–W_R mixing angles as small as 0.01. Figure 4 also shows the existing limits based on the muon decay experiments of Peoples[6,7] and Strovink,[8] and the limit expected when the analysis of a new ρ measurement at Los Alamos is completed,[9] as well as the limit from the direct search from D0.[10] If no assumptions are made about the form of the right-handed CKM matrix, E614 is sensitive to new particles with masses up to 740 GeV/c^2 and mixing angles as small as 0.012. In this case, the limits from D0 and Strovink are much weaker than shown in Figure 4.

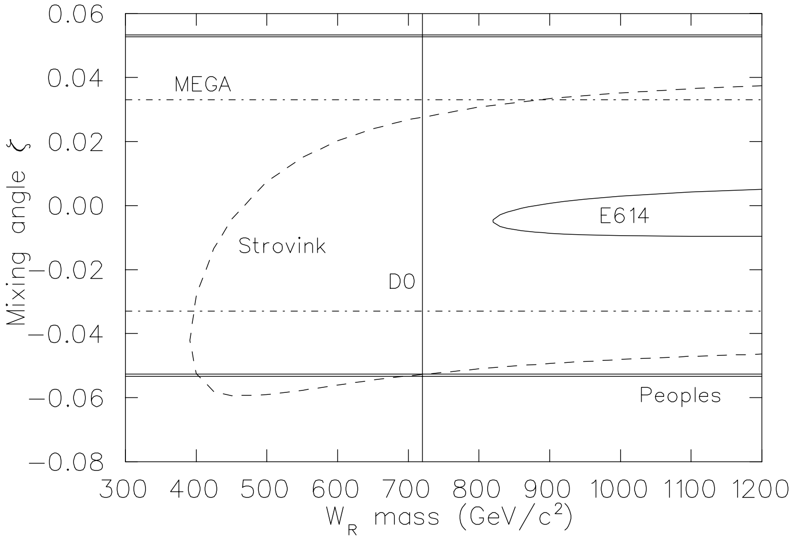

Figure 4: Current and proposed 95% CL limits on W$_R$ mass vs. mixing angle. Solid vertical line: W$_R$ mass limit from D0[10] assumimg $g_R = g_L$ and $V^R = V^L$. Solid curve: allowed region from E614 under the same assumptions. Dashed curve: allowed region from Strovink et al.[8] Dot-dashed lines: expected limits on mixing angle for M$_R$ infinite, from MEGA.[9] Double solid lines: mixing angle limits from Peoples et al.[6,7]

These limits can be put into context by comparing them to other experimental results. With the exception of muon decay studies, essentially all experimental tests of left-right symmetric theories are sensitive to the form assumed for the right-handed CKM matrix. For example, the well-known limit that M_R >1.6 TeV, based on the K_L–K_S mass difference,[11] only holds for *manifest* left-right symmetry, in which the left- and right-handed CKM matrices are assumed to be identical. By contrast, Langacker and Sankar[12] critically reviewed all the existing experimental limits as of 1989. They found that classes of models with either $V^R_{ud} \approx 1$ or $V^R_{us} \approx 1$ are consistent with M_R as light as 300 GeV, without "fine-tuning" the parameters. They also determined that the current muon decay results provided the most stringent limits on M_R and ζ for a broad class of left-right symmetric models, especially those in which

$V_{us}^R \approx 1$. E614 will significantly extend the limits in these cases.

4 Time-line for the Experiment

E614 was approved with high priority by the TRIUMF Experiments Evaluation Committee in July 1996, and was given final funding approval in April 1998. The pre-production prototype of the precision wire chamber package is under construction (Spring of 1999), with test beam scheduled for the summer of 1999.

Final assembly is expected to begin in the fall of 1999, with the experiment "on the floor" in January, 2001.

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