$\mathcal{TWIST}$ - The TRIUMF Weak Interaction Symmetry Test The Michel parameters from μ^+ decay

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We propose to make the first high precision measurements of nearly the entire differential spectrum (in energy and angle) of positrons from the decay of polarized muons. The main goal of the experiment is the precise testing of the $(V-A)$ structure of electroweak interactions in the framework of the $SU(2)_L \times U(1)$ model.

Highly polarized "surface" μ^+ from the TRIUMF M13 beamline will enter a large volume, high field superconducting magnet on axis and will stop in a thin target at its center. The e^+ from the muon decay will be precisely tracked in the magnetic field using small-cell planar drift chambers. This spectrometer has been simulated with GEANT and EGS4 and has been demonstrated to meet the precision requirements.

1. Background

The Standard Model of the strong, weak and electromagnetic interactions, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, has proven to be remarkably successful in describing the existing experimental observations. At present, there exist no experimental results that deviate from its expectations, with the exception of neutrino oscillation studies. However, the Standard Model is universally believed to be an incomplete theory of nature in spite of its many successes.

Normal muon decay $\mu \to e\nu\overline{\nu}$ is an ideal system

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	Accepted Value	Standard Model Value	TWIST Precision
ρ	0.7518 ± 0.0026	$\frac{3}{4}$	± 0.0001
δ	$0.7486 \pm 0.0026 \pm 0.0028$	$\frac{3}{4}$	± 0.00014
$P_\mu \xi$	$1.0027 \pm 0.0079 \pm 0.0030$	1	± 0.00013
η	-0.007 ± 0.013	0	± 0.003

Table 1
The accepted values of the Michel parameters[2] along with the Standard Model values.

with which to investigate the space-time structure of the weak interaction. This comes about because the purely leptonic nature of this decay eliminates any uncertainties due to the internal structure of the particles or contributions from other interactions.

For example, the Michel spectrum gives a model independent description of the energy and angular distributions of the $e^\pm$ emitted in the decay of polarized $\mu^\pm$. In the limit where the electron mass and radiative corrections are neglected[2] this spectrum is given by:

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

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

where θ is the angle between the muon polarization and the outgoing electron direction, $x = E_e/E_{max}$, and P_μ is the muon polarization. The three Michel parameters[1] ρ, ξ and δ completely determine the spectrum if neither the neutrinos nor the spin of the outgoing electron are observed. A fourth parameter η contributes to the energy spectrum when the electron mass is included in the analysis.

[2] In actually analyzing the data, radiative corrections will be applied to second order, and the electron mass will not be neglected.

In the Standard Model with pure (V-A) coupling, the four Michel parameters take specific values, as shown in table 1. The current experimental results [2] are consistent with these values. $\mathcal{TWIST}$ will determine ρ, δ, η, and $P_\mu \xi$ with significantly improved precision providing an excellent opportunity to observe physics outside the Standard Model if one or more of the measured Michel parameters differs from its expected value.

2. Apparatus

2.1. Spectrometer

The $\mathcal{TWIST}$ spectrometer, shown in Figure 1, comprises a 2 T super-conducting solenoid (originally employed for whole-body medical MRI) and a set of 44 precision planar drift chambers and 12 proportional chambers. A minimum bias trigger is obtained from a thin plastic scintillator read out using wave-length shifting fibres.

The muons are stopped and decay at the axis of the highly symmetrical detector system. This allows the simultaneous measurement of nearly the entire spectrum, allowing the extraction of the Michel parameters from data obtained under consistent conditions.

2.2. Detectors

A schematic view of a typical wire chamber plane is shown in Figure 2. The wires in the drift chambers are strung at 4 mm spacing, while those

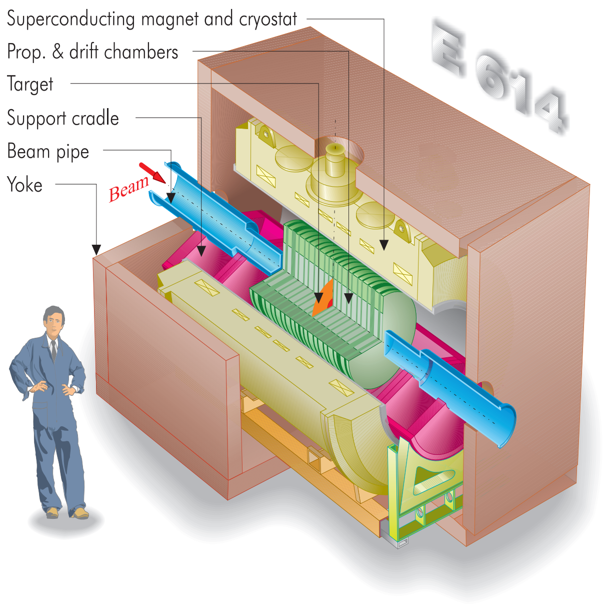

Figure 1. The *TWIST* spectrometer.

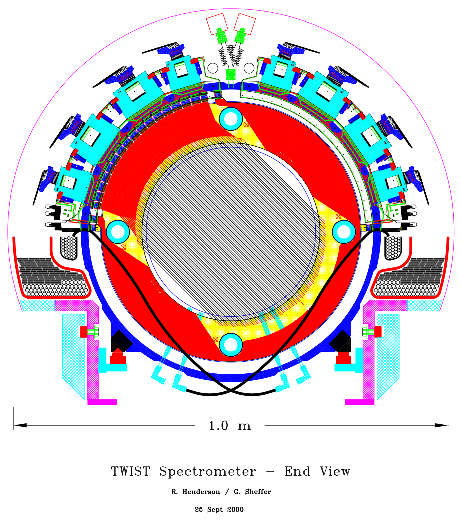

Figure 2. Schematic of one detector plane.

in the proportional chambers are at 2 mm spacing. The wires are strung on a surface referenced to a precision ground glass plate, which allows a precise definition of each wire plane.

The wire planes are strung on glass frames which are referenced to a column of ceramic-glass citals, as shown in Figure 3. These citals have a negligible coefficient of thermal expansion, and have been ground to high precision, allowing the spacing between any two wire planes to be defined to within a few microns on average.

To date, roughly 1/2 of the drift chambers have been strung. After stringing, each wire plane is subjected to quality control tests where tensions on each wire are measured and the position of the wires are measured with microscopes and CCD cameras. The measurements show that the wire positions are good to within a standard deviation of ≈ 3 microns.

2.3. The muon source

The most stringent demands are those relating to the preservation of muon polarization, which

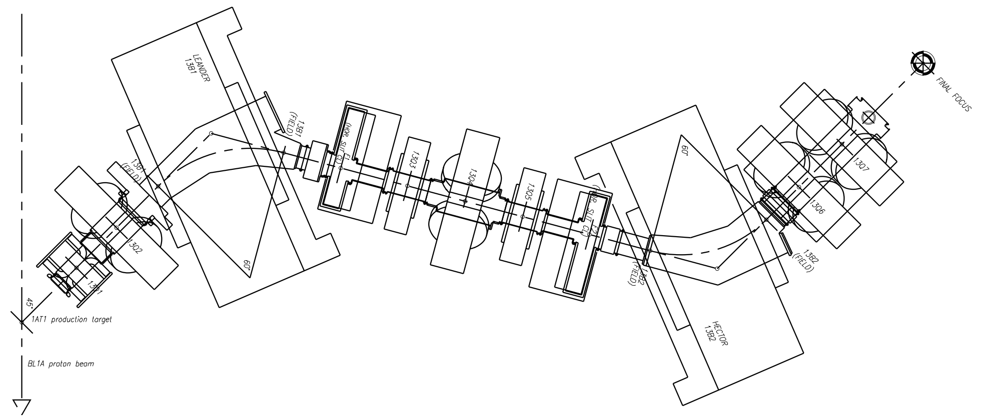

Figure 4. The M13 beamline at TRIUMF. The proton beam from the TRIUMF cyclotron passes from top to bottom along the left side of the figure. The $\mathcal{TWIST}$ spectrometer is placed at the focus of the secondary muon channel at the right.

is crucial to a precise measurement of one of the parameters describing the decay, ξ. As indicated by the expression for the double differential decay rate (Eq. 1), ξ appears only in the product $P_\mu \xi$, and an experimental limit can be placed only on this product. The Standard Model predicts that P_μ in the direction of the muon momentum vector is exactly -1 following pion decay at rest, due to conservation of angular momentum and the left-handedness of the muon neutrino. The experimental challenge lies in maintaining the polarization following pion decay, excluding as much as possible any muons which have undergone any processes which alter it, and predicting with high precision the degree to which they have been excluded. Sources of depolarization can be roughly categorized as *real*, which disturb the alignment between the muon spin and momentum vectors, and *apparent*, where the muon spin vector is not in perfect alignment with the direction of the magnetic field in the solenoidal spectrometer.

The $\mathcal{TWIST}$ spectrometer is coupled to the M13 low energy muon beam line at TRIUMF[3] shown in Figure 4. A surface muon beam results when pions are produced from 500 MeV protons striking a piece of graphite in vacuum. Some of the positive pions come to rest at or near the surface of the graphite. When they decay, muons can be emitted from the surface with energies up to the limit allowed by the two-body decay, depending on the energy lost in reaching the surface. Those within the angular and momentum acceptances of the M13 beam transport system form the highly polarized surface muon beam which is guided to the $\mathcal{TWIST}$ solenoidal spectrometer. No windows exist between the graphite surface and the entrance to the spectrometer, so scattering in this region is limited to residual gas interactions and slit-edge effects. This beam of *surface muons* is characterized by momentum up to 29.79 MeV/c (kinetic energy of 4.2 MeV), corresponding to a range of only 140 mg cm^{-2} in car-

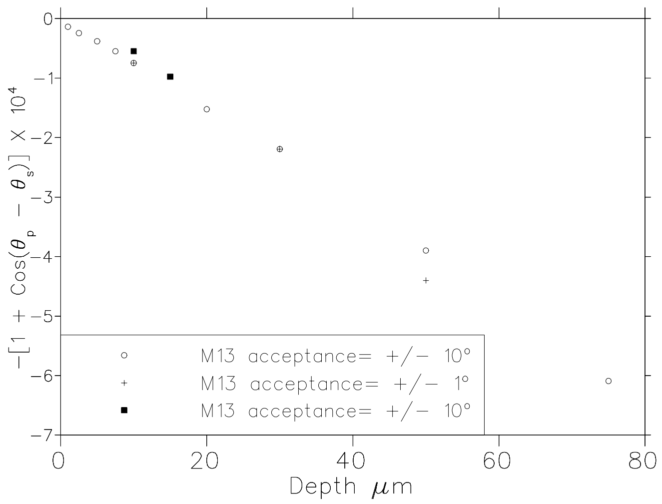

Figure 5. Muon "depolarization" in the 1AT1 Target. Here θ_p and θ_s are the final and initial momentum directions respectively. The hollow circles and crosses are the results when no momentum selection was made on the outgoing muon. The filled squares are the results when the outgoing momentum of the muon was restricted.

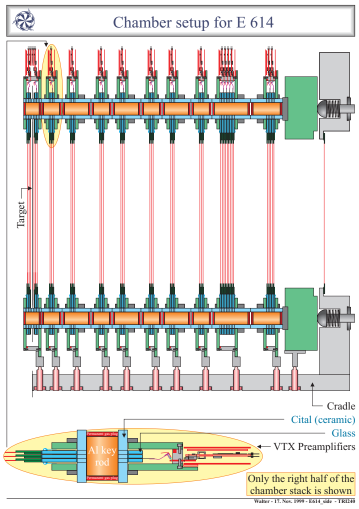

Figure 3. Half of the $\mathcal{TWIST}$ detector stack. The target - at the center of the detector - is shown at the left.

bon. The limited range of these muons makes it possible to use the momentum bite of the channel to select muons originating within tens of microns of the surface of the production target. These are muons which have undergone limited multiple scattering and their polarization is only slightly perturbed. Figure 5 shows this depolarization as a function of depth within the target of the original pion decay position.

Initial physics results will focus upon ρ and δ, since ρ does not rely upon the polarization of the muon beam, and the because the precise value of the polarization is not critical to the determination of δ. One analysis sensitive to δ involves analyzing the difference between the forward and backward data sets. The $\mathcal{TWIST}$ sensitivity to this distribution is shown in Figure 6.

3. Extraction of Physics

If the ultimate $\mathcal{TWIST}$ results are consistent with the Standard Model, they will permit us to set far more stringent limits than possible at present on those extensions to the Standard

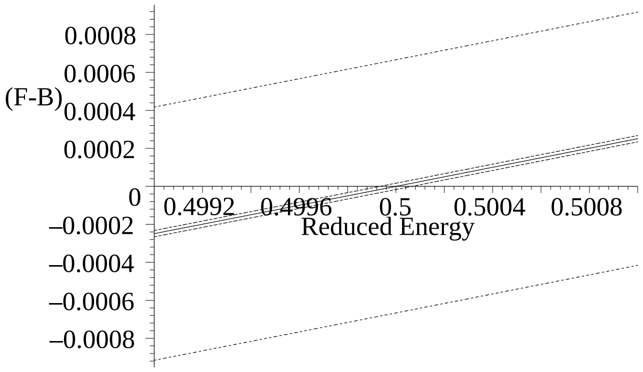

Figure 6. When the backward data is subtracted from the forward data, a distribution is obtained which is sensitive to δ. The (Forward-Backward) distribution is plotted above for a narrow region of energy. The central curve is the Standard Model, bounded by narrow limits from $\mathcal{TWIST}$. The outer curves show the existing limits on the shape of the distribution. Note that the curves in the figure have been generated in the limit of $m_e = 0$, and without inclusion of radiative corrections. These corrections will be included in the actual analysis.

Model that influence the space-time structure of the weak interaction. For example we will obtain new upper limits on the possible electroweak couplings from the above constraints. These anticipated new limits, shown in columns 2-5 of Table 2, were established by varying the magnitudes of the coupling constants independently from zero up to the current limit for each coupling, and the relative phases in the interference terms were varied from 0 to π. For each combination of couplings and phases which satisfied the constraints, maximum values of the couplings were found. In the first column, the limits as quoted by the Particle Data Group[2] are given.

In the most general case (D) - models which allow any Vector, Axial vector, Scalar, or Tensor derivative-free interactions - limits on all of the RR and LR couplings are improved over the current values while the RL and LL limits are not improved. 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 these latter 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

	Current Limits	$\mathcal{TWIST}$ (A)	$\mathcal{TWIST}$ (B)	$\mathcal{TWIST}$ (C)	$\mathcal{TWIST}$ (D)
$\lvert g^S_{RR}\rvert$	<0.066	—	—	<0.020	<0.045
$\lvert g^V_{RR}\rvert$	<0.033	<0.012	<0.014	<0.013	<0.022
$\lvert g^S_{LR}\rvert$	<0.125	—	—	<0.027	<0.046
$\lvert g^V_{LR}\rvert$	<0.060	<0.012	<0.013	<0.012	<0.018
$\lvert g^T_{LR}\rvert$	<0.036	—	<0.009	—	<0.013
$\lvert g^S_{RL}\rvert$	<0.424	—	—	—	—
$\lvert g^V_{RL}\rvert$	<0.110	<0.012	<0.012	<0.011	—
$\lvert g^T_{RL}\rvert$	<0.122	—	<0.008	—	—
$\lvert g^S_{LL}\rvert$	<0.55	—	—	—	—
$\lvert g^V_{LL}\rvert$	>0.96	>0.99977	>0.99953	—	—

Table 2
Upper limits (90% CL) for weak coupling constants with current limits taken from Ref. [2]. Anticipated improved limits set by $\mathcal{TWIST}$ based on 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.

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. $\mathcal{TWIST}$ will actually measure the quantity $P_\mu\xi$, and not ξ and P_μ separately. Since the surface muons employed by $\mathcal{TWIST}$ are produced in pion decay at rest, the value of the μ^+ helicity is equal to the ν_μ helicity, taken to be negative. For a measured value of $P_\mu\xi$ the allowed region in mixing angle-mass space is limited by[4]

$$\frac{1-P_\mu\xi}{4} = \zeta^2 + \frac{M_L^4}{M_R^4} + \zeta\frac{M_L^2}{M_R^2}. \tag{2}$$

Using this relation, the 95% CL limit for $P_\mu\xi$ from $\mathcal{TWIST}$ yields a lower limit for the W_R mass

$$M_R > 819 \ \ \mathrm{GeV}/c^2$$

and a limit on the range of ζ

$$-0.0096 < \zeta < 0.0083 \ .$$

When comparing these limits to those from other experiments it must be recalled that most experimental tests of left-right symmetric theories are sensitive to the form assumed for the right-handed CKM matrix. Muon decay studies have essentially no sensitivity to such assumptions. Thus limits established by $\mathcal{TWIST}$ will be complementary to, for example, the recent result from the D0 experiment: $M_R > 720$ GeV for $V^R_{ud} \approx 1$ ($V^R = V^L$)[5]. A $\mathcal{TWIST}$ result that indicated $M_R < 720$ GeV would raise questions regarding the D0 assumption about V^R_{ud}.

The above discussion was predicated on the assumption that the right-handed neutrinos are light, so they are not kinematically suppressed in muon decay. In this limit, lepton universality requires $|g^V_{LR}| = |g^V_{RL}|$, so δ retains its Standard Model value of 0.75. Alternative patterns for the three vector coupling constants appear in left-right symmetric models if one or both of the right-handed neutrinos are heavy. For example, if the right-handed muon neutrino is light, while the right-handed electron neutrino is heavy, g^V_{RR} and g^V_{RL} must both remain zero, while g^V_{LR} can be non-zero. This changes the relationships between ξ and ρ and ζ and M_R, and permits δ to deviate from its Standard Model value. A similar situation arises if only the right-handed electron neutrino is light. In fact, in this case, Herczeg noted [4] that $P_\mu \xi\delta/\rho$, the quantity measured by Strovink *et al.* [6], must remain identically equal to its Standard Model value of 1, while ξ, δ, and ρ may separately deviate from their respective Standard Model values. *This emphasizes the importance of a comprehensive investigation of all of the Michel parameters over a broad energy range, as will be provided by* $\mathcal{TWIST}$. If both of the right-handed neutrinos are heavy, g^V_{LR}, g^V_{RL} and g^V_{RR} must all remain zero.

The above discussion, while limited, indicates that an improved measurement of the Michel parameters of muon decay will have a significant impact on our understanding of the space time structure of the electroweak interactions and will impose strict limits on new particles and proposed extensions of the Standard Model.

4. Status

Production of the drift chamber planes began in the Spring of 2000, with roughly half of the drift chamber planes completed by the fall of 2000. In November 2000, a set of three UV pairs of production chambers was used with final production electronics to track cosmic ray particles and confirm performance. Production is continuing, and a full set of chambers is planned for completion by April 2001.

The magnet and return yoke will be installed on the M13 beamline at TRIUMF during the winter of 2000/01. The first engineering run is anticipated in April 2001.

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