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TWIST: TRIUMF WEAK INTERACTION SYMMETRY TEST

David R. Gill *
TRIUMF, 4004 Wesbrook Mall, Vancouver BC Canada V6T 2A3

Abstract

TWIST, the TRIUMF Weak Interaction Symmetry Test, has taken data in the first simultaneous precision measurement of the muon decay parameters ρ, δ, and $P_\mu\xi$. The ultimate goal of the experiment is to determine each of these parameters to a few parts in 10^4. With this precision TWIST will confront several proposed extensions to the Standard Model. For example, TWIST will be sensitive to right-handed W bosons with masses up to 800 GeV without needing to make assumptions about the form of the right-handed CKM matrix.

1 Physics of TWIST

The Standard Model(SM) of the strong, weak and electromagnetic interactions, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, has proved to be remarkably successful in describing the existing experimental observations. Despite this success the SM is universally believed to be an incomplete theory of nature.

* for TWIST collaboration

Normal muon decay $\mu \rightarrow e\nu\overline{\nu}$ is an ideal system with which to investigate the space-time structure of the weak interaction because the purely leptonic nature of this decay eliminates any uncertainties due to the internal structure of the particles or contributions from other interactions. A model independent description [1) 2)] of the energy and angular distributions of the $e^{\pm}$ emitted in the decay of polarized $\mu^{\pm}$ is provided in terms of four parameters, ρ, δ, η, and ξ. In the limit where the electron mass, neutrino mass and radiative corrections are neglected this spectrum is given by:

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

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 fourth parameter, η, appears in this equation when the electron mass is included in the analysis.

Table 1 presents the current experimental results [3)] for the Michel parameters and the precision to which TWIST aims to determine them. In the Standard Model with pure (V-A) coupling, the four spectrum shape parameters take the specific values presented in this table, the current results are consistent with these values.

If one or more of the measured parameters differs from its expected value it will constitute an observation of physics outside the Standard Model. For example, in left-right symmetric models [4)], a deviation in ρ from $\frac{3}{4}$ would imply that the mixing angle, ζ, between the W_R and W_L bosons of these models is non zero. A deviation of ξ from 1 provides a measure of the ratio of the squares of the W_R and W_L boson masses, the ultimate TWIST precision yielding a lower limit for the W_R mass of

$$M_R > 800 \ \ \mathrm{GeV}/c^2$$

When comparing such a limit 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. Equations 2, 3 and 4 display the sensitivity for β decay, $p\overline{p}$ collider and μ decay experiments respectively.

$$[\frac{g_R}{g_L}]^4 [\frac{V^R_{ud}}{V^L_{ud}}]^2 [\frac{M_L}{M_R}]^4 \quad (2)$$

Table 1: *The accepted values of the Michel parameters* [3] *along with the TWIST final precision and the Standard Model values.*

	Accepted Value	TWIST Final	SM Value
ρ	0.7518 $\pm$ 0.0026	$\pm$0.0002	$\frac{3}{4}$
δ	0.7486 $\pm$ 0.0026 $\pm$ 0.0028	$\pm$0.0003	$\frac{3}{4}$
$P_\mu\xi$	1.0027 $\pm$ 0.0079 $\pm$ 0.0030	$\pm$0.0004	1
η	-0.007 $\pm$ 0.013	$\pm$0.01	0

$$[\frac{g_R}{g_L}]^2[\frac{V_{ud}^R}{V_{ud}^L}]^2 Function[\frac{M_L}{M_R}] \tag{3}$$

$$[\frac{g_R}{g_L}]^4[1+[\frac{V_{ud}^R}{V_{ud}^L}]^2][\frac{M_L}{M_R}]^4 \tag{4}$$

These formula display that there is a complementarity of results from such experiments, for example if TWIST results were to indicate a W_R mass in a range where the collider searches see nothing it would mean that V_{ud}^R may be very small.

The discussion thus far has assumed that the right-handed neutrinos are light, so they are not kinematically suppressed in muon decay. In models with general V, A interactions, deviations from pure $V-A$ can be described by three parameters, g_{LR}^V, g_{RL}^V, and g_{RR}^V, that specify the coupling strengths for right-handed electrons and muons. In the limit of light right-handed neutrinos lepton universality requires $|g_{LR}^V| = |g_{RL}^V|$, 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_{RR}^V and g_{RL}^V must both remain zero, while g_{LR}^V 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.* [5], 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 is provided by TWIST.* If both of the right-handed neutrinos are heavy, g^V_{LR}, g^V_{RL} and g^V_{RR} must all remain zero.

TWIST will also provide information on the more general extensions of the SM that include scalar and tensor interactions. For example, the linear combination

$$Q^\mu_R = \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \tag{5}$$

provides a model independent measure of the total right-handed contributions to muon decay.

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 in the absence of non SM results will impose strict limits on new particles and proposed extensions of the Standard Model.

2 Experiment

The TWIST detector, which is shown Side-View in Figure 1, consists of 44 high precision drift chamber planes [6] and 12 MWPC planes.

It is centered in a solenoid magnet that provides a uniform 2T field. The surface muon beam, which is highly polarized, enters from the left as shown and the detector components are thick enough to bring these μ's to rest in the stopping target at the center. The drift chamber planes shown here are at right angles to the magnetic field and each consists of 80 wires at 4mm spacing. The positions of the 5000 wires are known in longitudinal and transverse positions to better than 5 parts in 10^5. The decay positrons spiral, either to the left or right in this figure, through the drift chambers producing hits on the wires that are recorded by TDCs. These helical tracks are later analyzed to precisely determine the positron energy and angle.

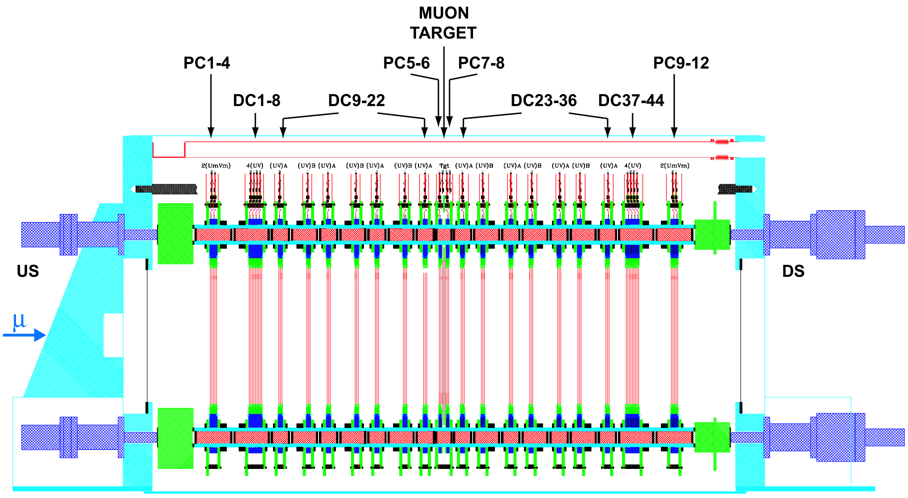

Figure 1: *Schematic of TWIST detector showing longitudinal arrangement of chamber planes. The stopped μ decays in the target at the center.*

The linearity of the decay spectrum in the shape parameters, as shown in Eq. 1, allows the employment of a blind analysis technique. The measured energy-angle spectrum is fit to the sum of a Monte Carlo generated spectrum for which the shape parameters are hidden, together with additional Monte Carlo distributions that describe the dependence on $\Delta\rho$, $\Delta\eta$, $\Delta\delta$, and $\Delta P_\mu\xi$. The Monte Carlo spectra are generated including the effects of the electron mass, plus the first- and many second-order radiative corrections not shown in Eq. 1.

3 Status

TWIST took data in the 2002 and 2003 with the goal of determining ρ and δ to 10^{-3}. TWIST is a systematics dominated experiment. Thus most of the beam time was used to collect data related to possible systematic effects with each effect amplified as much as practical. A total of 6×10^9 events were recorded to tape in sets of 3×10^8 events, each set being sufficient to determine ρ and δ to $\approx 6 \times 10^{-4}$. These independent sets explored the TWIST sensitivity to several categories of effects due to the beam properties, the detector performance, the magnetic field, the upstream-downstream symmetry of the system and overall system stability. Additional sets were taken to provide data to validate the quality of the GEANT-based Monte Carlo simulation.

The data analysis is now approaching completion and the results are very encouraging for a determination of ρ and δ to $\approx 10^{-3}$ level. The expectation is that the box containing the hidden values of the shape parameters will be opened shortly and that the first physics results from TWIST will be published in the fall of 2004.

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