Theoretical Implications of the TWIST Experiment Results

A. Hillairet[a,*]

[a] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada*

Abstract

The TRIUMF Weak Interaction Symmetry Test (TWIST) experiment measures the momentum and direction of the positron from the decay of polarized muons with very high precision. The TWIST results represent the world's most precise measurement of the muon decay spectrum. The experiment expects to meet its ambitious goals of an order of magnitude improvement over pre-TWIST results for the muon decay parameters ρ, δ and $P^{\pi}_{\mu}\xi$.

Our most recent published results combined with other experiments provide improved constraints on any deviations from the standard model. These results as well as the corresponding constraints on new physics are presented. The measures that have been taken to reduce the systematic uncertainties for the upcoming final result are described.

Key words: muon decay, weak interaction, Michel parameters, standard model
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1. Introduction

Muon decay is a purely leptonic process. The matrix element for the most general Lorentz-invariant, derivative-free, lepton-number-conserving matrix element M can be written in terms of helicity-preserving amplitudes as [1]

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{i=L,R \\ j=L,R \\ \kappa=S,V,T}} g^{\kappa}_{ij} \langle \bar{\psi}_{e_i} | \Gamma^{\kappa} | \psi_{\nu_e} \rangle \langle \bar{\psi}_{\nu_\mu} | \Gamma_{\kappa} | \psi_{\mu_j} \rangle, \tag{1}$$

where g^{κ}_{ij} are the complex weak coupling constants and Γ^{κ} are the possible interactions (scalar, vector, tensor). In this notation, the standard model (SM) postulates that $g^{V}_{LL} = 1$, and $g^{\kappa}_{ij} = 0$ otherwise. If the polarization of the decay positron is undetected, then the differential decay rate can be expressed as

$$\frac{d^2\Gamma}{dx\, d\cos\theta} \propto F_{IS}(x) + P_\mu \xi \cos\theta\, F_{AS}(x), \tag{2}$$

where $x = E_e/E_{\max.}$, $E_{\max.}$ is the maximum energy of the positron, θ is the angle between the muon polarization and the positron momentum, $P_\mu = |\vec{P}_\mu|$ (the degree of muon polarization), and

$$F_{IS}(x) = x(1-x) + \tfrac{2}{9}\rho\left(4x^2 - 3x - x_0^2\right) + \eta x_0 (1-x) + \text{R.C.}, \tag{3}$$

$$F_{AS}(x) = \tfrac{1}{3}\sqrt{x^2 - x_0^2}\left[1 - x + \tfrac{2}{3}\delta\left(4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right)\right] + \text{R.C.} \tag{4}$$

The R.C. terms are radiative corrections, which become more significant as x approaches one. x_0 is the dimensionless electron mass defined by $x_0 = m_e/E_{\max.}$. The muon decay parameters ρ, δ, ξ and η are bilinear combinations of the weak coupling constants. The TWIST experiment measures ρ, δ and $P^{\pi}_{\mu}\xi$ to parts in 10^4, where P^{π}_{μ} is the polarization of the muon from pion decay. The SM predicts that $\rho = \delta = 3/4$, $P^{\pi}_{\mu} = \xi = 1$, and $\eta = 0$; deviations from these predictions would indicate new physics.

*On behalf of the TWIST collaboration

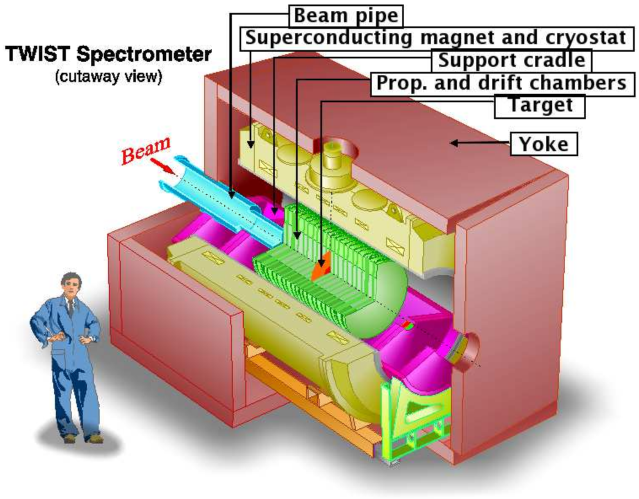

Figure 1: The TWIST spectrometer.

2. Experiment

The experiment was sited at the M13 channel at TRIUMF in Vancouver, Canada. Highly polarized positive muons were stopped in a thin metal foil at the center of a symmetric array of detectors within the bore of a solenoid that produced a uniform 2.0 T magnetic field known to 3 parts in 10^5. The particle identification relies mostly on 12 proportional chambers (PCs). The stopping target acts as a cathode foil in the center of a module of 4 PCs. Muons that stop in the target were selected using the PCs. The decay positron helices were tracked by 44 drift chambers, and their trajectories were later reconstructed to determine the positron's initial energy and angle. The wire positions were known to 5 parts in 10^5 providing a high reconstruction resolution of 60 keV at a positron energy of 52 MeV. The wire chambers were low mass to reduce multiple scattering. The decay positrons traverse a range of only 77 mg/cm^2. Further detail on the apparatus can be found elsewhere [2].

The muon decay parameters were measured by comparing the positron spectrum from the data to the positron spectrum from a `GEANT3.21` simulation that was subjected to the same analysis. In this way the detector response and reconstruction biases were accounted for within the simulation. Hidden values of ρ, δ and ξ were used in the simulation, and these were not revealed until corrections and systematic uncertainties had been evaluated on the *difference* in decay parameters between the data and simulation spectra; this technique provided a blind analysis by exploiting the spectrum's linearity in ρ, $P_\mu^\pi\xi$ and $P_\mu^\pi\xi\delta$ (see Eqs. (3),(4)).

Special data validated the positron physics in the simulation: muons were stopped close to the entrance of the detector; in this configuration the decay positrons traversed the whole detector. The corresponding tracks were independently reconstructed in each half of the detector, before and after crossing the stopping target. The differences in energy and angle between these two trajectories were in excellent agreement for data and simulation [3]. The reconstruction efficiency was also measured from this special data by counting the number of tracks reconstructed in one half of the detector but not the other.

3. Results

Our most precise results for the muon decay parameters are [3, 4]

$$\begin{aligned} \rho &= 0.75014 \pm 0.00017\,(\text{stat.}) \pm 0.00044\,(\text{syst.}) \pm 0.00011\,(\eta), \\ \delta &= 0.75067 \pm 0.00030\,(\text{stat.}) \pm 0.00067\,(\text{syst.}), \\ P_\mu^\pi\xi &= 1.0003 \pm 0.0006\,(\text{stat.}) \pm 0.0038\,(\text{syst.}). \end{aligned} \tag{5}$$

The parameter η is fixed to the world average value, which introduces an additional uncertainty through its correlation with ρ. The results are consistent with the SM. The improvements over the pre-TWIST results represent more than

	Pre-TWIST	Gagliardi *et al.*	MacDonald *et al.*
$\lvert g^S_{LR}\rvert$	< 0.125	< 0.088	< **0.074**
$\lvert g^V_{LR}\rvert$	< 0.060	< 0.036	< **0.025**
$\lvert g^T_{LR}\rvert$	< 0.036	< 0.025	< **0.021**

Table 1: Confidence limits (90%) on the weak coupling constants, from a global analysis of muon data.

a factor of five for ρ and δ [5, 6] and a factor of two more precise for $P^{\pi}_{\mu}\xi$ [7]. The ρ and δ results were limited in precision by uncertainties in the drift chamber response, while the $P^{\pi}_{\mu}\xi$ result was limited by the accuracy of simulating the depolarization.

4. Improvements for the final measurement

Final data were acquired in 2006 and 2007, with a higher quality muon beam and a threefold increase in statistics. The analysis of this data is nearing completion.

The space-time relationships (STRs) in the drift cells have been improved, by correcting them so that the fitting residuals are minimized. These improved STRs also corrected reconstruction biases. Each drift chamber was corrected independently; this accounted for small differences in construction and response. The beam line was upgraded to correct an undesirable muon beam vertical deflection of $\approx$ 1.0 cm. The beam was steered onto the symmetry axis of the solenoid, which reduced the uncertainty in simulating the depolarization. The long term stability of the beam was monitored using its average position measured by the wire chambers. Muons were stopped in both an Al and Ag target foil (previously only an Al foil was used).

5. Theoretical implications

The TWIST published results have already put stringent constraints on new physics. A global analysis combines muon decay results from different experiments, such as measurements of the transverse and longitudinal polarization of the outgoing electron, to extract limits on the weak coupling constants [8]. The joint probability distributions of a special set of bilinear combinations of the coupling constants are extracted using Monte Carlo integration techniques. The latest TWIST results have significantly improved the limits on three of the weak coupling constants as shown in Table 1).

The coupling constants can be used to establish a limit on the probability for the decay of a right-handed muon into a left- or right-handed positron. Prior to TWIST this was 0.51% (90% C.L.), and our latest results reduce the limit to 0.23%. In Left-Right Symmetric (LRS) models the right-handed current is suppressed. An additional heavy right-handed W-boson (W_R) is introduced to restore parity conservation at high energies [9]. The TWIST results allow model-independent limits on the parameters of the LRS models. The TWIST result for ρ allow for model-independent constraints on the mixing angle (ζ) between the W_L and W_R. The measurements of $P_\mu\xi\delta/\rho$ [10] [11] or $P_\mu\xi$ also constrain the mass m_2 of the mass eigenstate W_2. The pre-TWIST limits from muon decay were $|\zeta| < 0.047$ and $m_2 > 294\text{GeV}/\text{c}^2$ in the case where $g_L = g_R$. These are now improved to $|\zeta| < 0.022$ and $m_2 > 364\text{GeV}/\text{c}^2$. The TWIST final results will further improve the constraints on models beyond the SM.

6. Conclusions

The TWIST results have already improved constraints of models beyond the SM. The experiment is on course to achieve an order of magnitude improvement over the pre-TWIST results for ρ, δ and $P^{\pi}_{\mu}\xi$. The dominant systematic uncertainties have been reduced, and the final results are expected in early 2010.

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