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To cite this article: R Bayes and (on behalf of the TWIST Collaboration) 2013 J. Phys.: Conf. Ser. 408 012071

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The final measurements of the muon decay parameters from the TWIST experiment

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Abstract. The TWIST (TRIUMF Weak Interaction Symmetry Test) experiment probes the Lorentz structure of the weak interaction using muon decay. This structure has a very well defined form under the Standard Model (SM) which makes precise predictions for the shape of the decay positron spectrum with respect to momentum and angle. The shape of the spectrum may be described under some rather general assumptions using a set of decay parameters whose values according to the SM are $\rho = 3/4, \delta = 3/4, \eta = 0,$ and $\xi = 1$. TWIST uses a large sample of muon decays in a large acceptance spectrometer to measure the decay parameters to an order of magnitude greater precision than previous measurements. This experiment saw its last year of data collection in 2007. As TWIST is a systematics dominated experiment, much effort has been spent on refinements of the estimates of the systematic uncertainties over previous TWIST results. These proceedings will discuss the measures taken to achieve the precision goal of parts in $10^4$, and the physics implications of the experiment.

1. Introduction

In the standard model (SM) the weak interaction moderates charge current interactions between fermions via the $W^\pm$ boson with a $V - A$ coupling. This structure of the SM weak interaction is based on observation, so it is essential to actively test this behaviour. The TRIUMF Weak Interaction Symmetry Test (TWIST) was conceived as a direct test of the weak interaction using the positron spectrum of the muon decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$. Prior measurements were completed by TWIST in 2004 [1, 2], 2006 [3], and 2008 [4]. These proceedings describe the recently published final measurement of the TWIST experiment [5, 6].

The generalized, Lorentz invariant, derivative free, four fermion point interaction is described by the matrix element [7]

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} g_{\mu}^\gamma \langle e_\epsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_{\epsilon} | \mu_\mu \rangle$$

(1)

where a $\mu$ handed muon couples to an $\epsilon$ handed positron via a scalar (S), vector (V), or tensor (T) interaction with a coupling strength $g_{\mu}^\gamma$. The neutrino chiralities, $n$ and $m$ are dictated by the type of coupling that occurs. The $g_{\mu}^\gamma$ represent 19 free parameters in the system as they are complex constants, assuming unitarity and that $g_{RR}^T = g_{LL}^T \equiv 0$. In the SM all $g_{\mu}^\gamma$ are zero with the exception of $g_{LL}^V = 1$.

The positron spectrum from muon decay is given by the differential distribution [8]

$$\frac{\partial^2 \Gamma}{\partial x \partial \cos \theta} = \frac{m_{\mu}}{4\pi^3} W_{e\mu}^4 G_F^2 \left( F(x) + \tilde{P}_\mu \cos \theta G(x) \right)$$

(2)
where \( x = E_e/W_\mu \) is the reduced momentum when \( W_\mu = 52.83 \text{ MeV}/c \) is the maximum energy of the decay positron, and \( \theta \) is the angle between the muon polarization and positron direction, \( \cos \theta = \vec{P}_\mu \cdot \vec{P}_e/|\vec{P}_\mu||\vec{P}_e| \). \( F(x) \) and \( G(x) \) are tree level isotropic and anisotropic spectra,

\[
F(x) = \sqrt{x^2 - x_0^2} (x(1-x) + \frac{2}{9} \rho (4x^2 - 3x - x_0^2) + \eta x_0 (1-x)) + \text{R.C.} \tag{3}
\]

\[
G(x) = \frac{1}{3} \xi (x^2 - x_0^2) \left( 1-x + \frac{2}{3} \delta \left( 4x - 3 + \left( \sqrt{1 - x_0^2} - 1 \right) \right) \right) + \text{R.C.} \tag{4}
\]

where \( \rho, \eta, \delta, \) and \( \xi \) are the muon decay parameters. The decay parameters are bi-linear combinations of the weak coupling constants, and \( \rho = \delta = 3/4, \xi = 1 \) in the SM. TWIST was not sensitive to the \( \eta \) parameter.

The goal of the TWIST experiment was to improve the precision of \( \rho, \delta, \) and \( P_\mu \xi \) by an order of magnitude over previous experiments. To achieve this level of precision all radiative corrections, denoted as R.C. in Eq. 3 and 4, up to the second order leading logarithmic corrections \( \mathcal{O}(\alpha^2 \ln^2) \) were included in the analysis [9]. The second order correction \( \mathcal{O}(\alpha^2) \) was not included in the analysis and is a systematic uncertainty.

2. The TWIST apparatus

TWIST was conducted at TRIUMF in Vancouver, B.C., using the 500 MeV cyclotron to produce surface muons from a graphite target. Surface muons, with polarization \( P_\mu = 1 \) in the SM, were transported with no depolarization down the M13 secondary beamline into the TWIST experimental area. The primary apparatus was a parallel plane spectrometer immersed in a 2 Tesla solenoidal magnetic field which is known to a precision of 0.5 Gauss. The final focus of the beamline was immediately before the spectrometer along the magnetic field axis to minimize muon depolarization. A pair of low mass, time expansion chambers (TEC) were periodically introduced in the beamline at its focal point to monitor the beam position and angle.

The TWIST spectrometer was composed of 44 planar drift chambers (DC) and 12 planar proportional chambers (PC) with a scintillator system upstream of the spectrometer providing a muon event trigger [10]. The chambers are arranged symmetrically around a 99.999% pure Al or Ag muon stopping target foil. The stopping position of the muons was controlled using a variable density gas degrader coupled to a software feedback system which maintained the mean position of the stopping distribution at the micron level in the target foil. The detector dimensions and wire positions were known to a precision of parts in \( 10^8 \) in all three dimensions allowing for a high precision measurement of the passage of positron tracks.

3. Analysis

The data used by TWIST for the purpose of this analysis were \( 10^{10} \) muon events collected in 14 sets wherein the experimental conditions were held constant. Analysis of single muon decay events begin with pattern recognition using PC hit times and simple fits using DC wire centres. Momenta and angles describing the helical positron path are extracted from a least squares fit using the closest distance of approach to the wires supplied by tabulated DC space time relationships. Cuts and event selections are applied to the data to identify events with low systematic bias. A total of \( 5 \times 10^8 \) high quality events were identified after cuts.

The measurement of the muon decay parameters (MDPs) relies on a very good Monte Carlo simulation (MC) of muon decays within the TWIST detector. This MC was generated from pre-defined samples of muon decay spectra input to a GEANT 3 simulation of the detector. These samples were defined using a randomly selected set of MDPs which were hidden from the experimenters. The value of \( \eta \) was fixed to \( -0.0036 \pm 0.0009 \) [4]. The simulation was generated with 2.7 times the number of events in data. The MCs were subjected to the same analysis as the
data. The data spectrum was fit to a linear combination of the simulated spectrum and a set of “derivative” spectra with a $\chi^2$ statistic to determine the difference in the MDPs $\rho$, $\delta$, and $\xi$. This approach is possible because spectrum has a linear dependence on the muon decay parameters. The difference in momentum scales between data and MC is angle dependent and significant relative to the precision goals of TWIST; $\Delta p/W_{\mu} \sim (10 \text{ keV/c })/52.828 \text{ MeV/c } \sim 2 \times 10^{-4}$. The momentum calibration was corrected in the data by removing the linear interpolation of the differences with respect to $1/|\cos \theta|$ from each event. The nature of this correction as a function of momentum is unknown so its implementation was a systematic uncertainty. Two different calibration methods were used: a momentum shift $p_{ec} = p_{raw} + \Delta p$, and a scaling $p_{ec} = p_{raw}/(1 - \Delta p/W_{\mu})$. MDPs were taken to be the average value from the two methods.

4. Systematics
TWIST is a systematics limited experiment so a majority of effort in the experiment was spent controlling and understanding systematic effects on the decay spectrum. The systematic uncertainties are shown in Fig.1. Systematics are categorized as target material specific, common to all data sets, and specific to measurements involving the polarization. The positron interaction systematics are examples of the systematic evaluation. The difference between data and MC is less than 1% for delta ray production and 2.4% for bremsstrahlung production. The uncertainties in the muon decay parameters were measured from special MCs which exaggerate the effect of these positron interactions fit to a nominal MC. MDP differences from this fit, scaled relative to the interaction difference between data and MC, are the systematic errors.

5. Physics results
The measured values of the decay parameters are shown in Table 1. The best measurements completed prior to the TWIST experiment are also shown demonstrating that the experimental goals of the experiment were achieved. The precise data set needed to be selected by the

| Systematic Uncertainties (%) | $\rho$ | $\delta$ | $\xi$ |
|-----------------------------|-------|--------|------|
| Ag Thickness/stop position   |       |        |      |
| Al Thickness/stop position   |       |        |      |
| Al Statistical               |       |        |      |
| Depolarization, fringe field |       |        |      |
| Weighted total systematic    |       |        |      |
| Weighted total statistical   |       |        |      |

Figure 1: Graphical representation of the systematics for the parameters $\rho$, $\delta$, and $\xi$.

Table 1: MDPs values measured from this work in contrast to the previous best measurements.

| Systematic Uncertainties (%) | $\rho$ | $\delta$ | $\xi$ |
|-----------------------------|-------|--------|------|
| Current work                | 0.74997 ± 0.00012 | 0.75049 ± 0.00021 | 1.00084 ± 0.00029 |
| Previous results            | 0.7518 ± 0.0026 | 0.7486 ± 0.0038 | 1.0027 ± 0.00085 |

Table 2: Coupling constants determined from the global analysis of the MDPs.

| $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|---------|---------|---------|
| 0.035   | 0.017   | 0.105   | 0.105   | 0.960   |

| $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|---------|---------|
| 0.050   | 0.023   | 0.015   | 0.105   |

| $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|---------|
| 0.420   | 0.105   | 0.105   |

| $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|---------|
| 0.550   | 0.960   | 0.960   |

| $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|---------|---------|
| 0.035   | 0.017   | 0.105   | 0.105   |

| $|g_{LR}|$ | $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|---------|
| 0.050   | 0.023   | 0.015   |

| $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|
| 0.420   | 0.105   |

| $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|
| 0.550   | 0.960   |

| $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|
| 0.035   | 0.017   |

| $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|
| 0.050   | 0.023   |

| $|g_{LR}|$ |
|---------|
| 0.420   |

| $|g_{LR}|$ |
|---------|
| 0.550   |

| $|g_{LR}|$ | $|g_{LR}|$ |
|---------|---------|
| 0.035   | 0.017   |

| $|g_{LR}|$ |
|---------|
| 0.050   |

| $|g_{LR}|$ |
|---------|
| 0.420   |

| $|g_{LR}|$ |
|---------|
| 0.550   |
collaboration with an agreed analysis such that the results needed to show good internal consistency and the systematics needed to be similarly agreed upon by all members of the collaboration before the analysis was completed and the hidden parameters were revealed. All criteria were satisfied and the hidden parameters were revealed on January 22, 2010. The measured value of the combination of parameters $P_μξδ/ρ$ is greater than 1 by 2.9σ, implying that the spectrum is not positive definite for a small region at the endpoint outside of the fiducial region. This is not physical, initiating an internal review of the results. The review resulted in the separation of the systematics into stopping target dependent and common, with an associated re-weighting of the average decay parameter to accommodate this change. A systematic uncertainty pertaining to the the mean muon stopping position was identified. There was very little change in the MDPs after the review with a small change in $P_μξδ/ρ$. A global analysis was used to evaluate the effect of these new measurements on the weak couplings[14]. The three MDPs measured here are not sufficient on their own to constrain the values of the weak coupling constants so parameters from decay positron polarization measurements [15, 16] were included with current and past measurements of $ρ$, $δ$, and $P_μξ$ as shown on Table 1. Table 2 shows the weak coupling constants where there is improvement in the right-right and right-left coupling constants. Further improvements in limits on left-right coupling constants require inverse muon decay measurements. A lower limit $P_μξδ/ρ > 0.99909$ was set from the global analysis.

6. Conclusions

The measurement of the MDPs is used as a model independent test of the SM weak interaction. TWIST completed its measurement of the three MDPs $ρ$, $δ$, and $P_μξ$ in 2010, having achieved its stated goal of an order of magnitude improvement in precision over previous measurements. The value of the endpoint anisotropy $P_μξδ/ρ$ calculated from these results produced a non-physical result and so prompted a review of the experimental analysis of the collaboration after the hidden parameters were revealed, but no errors in the analysis were found that could explain the inconsistency. In spite of this the experiment makes a significant contribution to the limits of the weak interaction couplings.

Acknowledgments

All TWIST collaborators and students deserve profound thanks for their efforts in producing these results. This work was supported in part by the National Science and Engineering Research Council and the National Research Council of Canada, the Russian Ministry of Science, and the U.S. Department of Energy. Computing resources were supplied by WestGrid and Compute/Calcul Canada.

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