NSERC Site Visit Report
TWIST-E614 Experiment at TRIUMF (Project Grant)
Applicant: Dr. Glen Marshall

February 5, 2004

1. INTRODUCTION

1.1 Site visit

The *TWIST* review committee of NSERC met at TRIUMF on January 14-15, 2004. A variety of presentations were delivered by *TWIST* collaboration members (the agenda is attached). The committee consisted of John Carr (CNRS-Marseille), Martin Cooper (Los Alamos), Richard Hemingway (Carleton), Dean Karlen (Victoria), Mark Strovink (U.C. Berkeley, chair) and Rick Van Kooten (Indiana). In attendance was Kate Wilson of NSERC. The committee also met with TRIUMF director Dr. Alan Shotter.

1.2 Review history

Following a conceptual design by the Russian group of Selivanov *et al.* in 1991, *TWIST* (aka E614) was proposed at TRIUMF in 1993 and, after a detailed review at the request of the EEC, was given the green light to proceed. A further review in 1996, requested by NSERC, recommended a level of funding for a 3-year period that would allow the experiment to be constructed. Funds were allocated by NSERC in April 1998, and DOE provided funds for the US groups.

NSERC reviewed *TWIST* again in December 2001. At that time the *TWIST* experiment had been assembled and commissioned and preliminary data had been taken. The group was awarded a 1-year operating grant of $475,000 and a computing equipment grant of $90,000. The last review by NSERC was in January 2003 to evaluate a new 3-year grant application. In awarding a 2-year grant of $475,000 per annum, the GSC recommended another review mid-term, which is the subject of this report.

1.3 Charge

This committee was charged "to determine whether sufficient progress has been made identifying systematic effects and how to address them, on the way to measuring ρ and δ to 10^{-3}, that measuring the [muon decay] parameters to a precision of 3×10^{-4} is still feasible for the experiment."

2. OVERVIEW

2.1 Physics objectives

The purely leptonic decay of the muon, $\mu \to \nu_\mu e\bar{\nu}_e$, provides an ideal opportunity to investigate the spacetime structure of the charged-current weak interaction. Neglecting radiative corrections, the differential decay distribution of the μ^+ conventionally is expressed in terms of four Michel parameters via

$$\frac{d^2\Gamma}{x^2\,dx\,d\cos\theta} \approx 3\big(1+\boldsymbol{\eta}\frac{x_0}{x}\big)(1-x)+\tfrac{2}{3}\boldsymbol{\rho}(4x-3)+\boldsymbol{\xi}\mathcal{P}_\mu\cos\theta\big[1-x+\tfrac{2}{3}\boldsymbol{\delta}(4x-3)\big]\ ,$$

where x is the positron energy normalized to its maximum value $E_{\max}$, $x_0 = m_e/E_{\max}$, $\mathcal{P}_\mu$ is the muon polarization, and θ is the angle between the polarization vector and the positron direction.

In the Standard Model (SM), the Michel parameters ρ, η, δ, and ξ are expected to be equal, respectively, to $\frac{3}{4}$, 0, $\frac{3}{4}$, and 1. In the *TWIST* experiment, beam muons arise from pion decay at rest; in the SM the daughter μ^+ helicity is expected to be $\vec{\mathcal{P}}_\mu \cdot \hat{p}_\mu = -1$.

Previous experiments (*ca.* 1969, 1985-88) have shown that the SM $(V-A)$ amplitude structure for this weak interaction is in good agreement with data. Current best values for the Michel parameters are

$$\begin{aligned} \rho &= 0.7518 \pm 0.0026 \ \ \text{(1969 publication)} \\ \eta &= -0.007 \pm 0.013 \ \ (1985) \\ \delta &= 0.7486 \pm 0.0038 \ \ (1988) \\ \xi\mathcal{P}_\mu &= 1.0027 \pm 0.0085 \ \ (1987) \\ 1 - \xi\mathcal{P}_\mu\frac{\delta}{\rho} &< 0.00318 \ \ (90\% \text{ confidence, } 1986)\ . \end{aligned}$$

The emphasis today is to look for deviations from these SM expectations in order to reveal physics possibilities beyond the SM. *TWIST* proposes to improve the accuracy of the parameters ρ, δ, and $P_\mu\xi$ by at least an order of magnitude (*i.e.* from $\approx 3\times10^{-3}$ to $\approx 3\times10^{-4}$), and the accuracy of η by a factor of three. If the experiment is successful, the improved results either will reveal new physics or will significantly tighten the existing constraints on several classes of model which propose new physics beyond the SM. For example, in classes of left-right symmetric models, the reach in right-handed W mass of *TWIST* is $\mathcal{O}(1\ \text{TeV}/c^2)$ (comparable to the ultimate expectation for the Fermilab Tevatron), and the *TWIST* reach in the W_R-W_L mixing angle is $\mathcal{O}(10\ \text{mrad})$. In conjunction with other precision experiments that are exploring potential SM discrepancies, the *TWIST* results may point the road to new fundamental physics.

2.2 TWIST summary

At TRIUMF, pions are produced when the 500 MeV cyclotron's proton beam strikes a target (*TWIST* has used a water-jacketed Be target). Some of the π^+ come to rest near the surface of the target and decay to muons. These μ^+ are transported in vacuum via the M13 beam line and enter the *TWIST* spectrometer on axis. The spectrometer comprises a nearly uniform 2 Tesla superconducting solenoid and a set of 44 precision-built drift chambers and 12 proportional chambers, accurately positioned along the spectrometer axis. A minimum bias trigger is obtained from a thin plastic scintillator near the upstream end of the solenoid.

The incoming μ^+ is stopped in a special target at the center of the spectrometer and the decay e^+, which follows a helical trajectory in the magnetic field, is tracked via the symmetrical wire chamber system upstream and downstream of the stopping target. With precise chamber alignment and carefully mapped field, both the positron energy and direction can be measured over a significant portion of the phase space for $\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$. A particular experimental challenge for the measurement of $\xi\mathcal{P}_\mu$ is to control the system (π^+ target, M13 channel, stopping target, spectrometer) such that the μ^+ polarization at production is maintained until the μ^+ decays.

TWIST is able to record data at a rate up to 5 kHz, yielding large data sets and suitably small statistical errors. Its real challenge, to determine Michel parameters with a precision of $\approx 3\times10^{-4}$, will be the understanding and control of systematic errors. Previous reviews have identified this challenge as the most important characteristic of the experiment.

2.3 Twelve month progress summary

Over the last 12 months significant progress has been made by the TWIST collaboration towards the goal of determining ρ and δ to a precision of 10^{-3}. With the very recent advent of the WESTGRID computing facility at UBC, much of the data recorded in 2002 and 2003 have been processed through a vastly improved analysis package. In addition, following many earlier studies of beam and detector behavior, an upgraded GEANT3 simulation package has allowed the creation of corresponding Monte Carlo (MC) datasets. Furthermore, a methodology has been developed and tested whereby the reconstructed data can be analyzed to determine the muon decay (Michel) parameters in an unbiased way using a blind technique. This methodology also provides the ability to estimate the important systematic errors from a comparison of data-to-data and MC-to-MC datasets that incorporate excursions of one or more sensitive experimental variables.

The initial prognosis is encouraging. Notwithstanding the preliminary nature of the very recent results (WESTGRID started production processing only in early November 2003), they do stimulate anticipation that the goal of $\approx 10^{-3}$ precision with the existing data is within reach. No show-stoppers have yet been identified.

It was remarked that, following some recent staff movements, with the appointment of a TRIUMF Research Scientist, the transfer of an RA from another TRIUMF group, and the search for another RA, the TWIST team will soon regain its previous strength, provided that Ph.D. students graduating in the next 1-2 years can be replaced.

During 2003 the collaboration has pursued some of the experimental tasks that are thought to be critical if a precise determination of $\xi\mathcal{P}_\mu$ is to be achieved. These tasks include construction of a pure Al foil stopping target, precise mapping of the magnetic field in the beam entrance region of the spectrometer, the study and implementation of a new M13 beam tune, and the construction of a low-mass Time Expansion Chamber (TEC) for precise monitoring and characterization of the muon beam. All of these features are relevant to establishing the best running conditions (production target and M13 transport) such that muon depolarization is minimized and calculable.

3. BEAM

TWIST requires the uncertainty in average M13 beam polarization $\langle\mathcal{P}_{\text{beam}}\rangle$ not to dominate its anticipated uncertainty on measured $\xi\mathcal{P}_\mu$. For the 2002 data, muons stopped in TWIST turned out to be depolarized by $\mathcal{O}(10^{-1})$ in a carbon coated mylar foil target that since has been replaced by pure Al. Therefore, for the 2002 data, the exact value of $\langle\mathcal{P}_{\text{beam}}\rangle$ and its uncertainty are of interest only as predictors of future running conditions, and $\xi\mathcal{P}_\mu$ will not be measured at or near the originally anticipated sensitivity.

By the time of a short data collection period in late 2003, the fields in most M13 magnets had been finely regulated, and a tune of the type proposed for TWIST had been further refined and implemented. A rough check indicates that the 2003 beam was fully polarized to within $\approx 1\%$. Unfortunately, relative to the requirements of this and similar tunes, the beam emittance was too large; after entry into the TWIST solenoid, the beam depolarization is calculated to have been no smaller than $\approx 4 \times 10^{-3}$. Possibly its uncertainty may still permit a ξP_μ measurement at the few $\times 10^{-3}$ level from the 2003 data.

For the M13 beam emittance to be reduced to the desired level, for which an optimized tune predicts $1 - \langle P_{\text{beam}}\rangle \approx (4 \pm 1) \times 10^{-4}$ after it enters the TWIST solenoid, a bare 2 mm carbon target will be needed. The 2002 and 2003 beams employed a much larger water-cooled target, used because radioactive particles otherwise evaporate from the target, migrate close to the TWIST detector volume, and overwhelm the chambers. To take advantage of the 2 mm target in any future running, a thin foil barrier will need to be inserted in the M13 beamline upstream of *TWIST*, introducing further energy loss, scattering, and depolarization that are calculated to be tolerable. Also, TRIUMF's operating current may need to be reduced ≈ 20% to 100-120 μA.

A Time Expansion Chamber (TEC) for insertion upstream of the *TWIST* solenoid has been constructed at TRIUMF. As anticipated, it is too massive to be compatible with standard data collection. Nevertheless, if the TEC is succesfully commissioned, inserting it for special runs should permit much more frequent monitoring of the average M13 beam phase space.

4. DETECTOR PERFORMANCE

Apart from a report on detector alignment, at the review the operational performance of *TWIST* was not discussed in detail. In general the tracking system has performed very well, with all chamber planes operational and highly efficient. A key requirement of the experiment is to understand and correct any misalignments in the drift chamber planes that could distort the the momentum or angular distributions as measured by the experiment. The procedures for alignment have been demonstrated and found to improve the residual distributions substantially. From MC studies, the remaining misalignment is expected to result in systematic uncertainties in the Michel parameters below the 10^{-3} level. In the future, the experimenters expect to sharpen their estimates of these uncertainties by reconstructing the *same* MC events using different alignment constants.

5. ANALYSIS

5.1 Track reconstruction

Impressive progress has been made by the *TWIST* collaboration on tracking algorithms and software. Starting from multihit TDC tracking information, δ rays are now effectively removed to reduce pattern recognition confusion. Two independent pattern recognition algorithms are > 99% efficient over ≈ 20% of the muon-decay phase space ($20 < p < 50$ MeV/c and $0.54 < |\cos\theta| < 0.8$), and allow mutual comparisons as well as the potential for future combination. Efforts continue on improving the pattern recognition algorithms to expand this fiducial region and optimize the tradeoff between statistical and systematic errors due to track misreconstruction.

Following the grouping of hits onto tracks, the inclusion of energy loss and kinks due to multiple scattering at each detector plane as constraints in the helix fits have represented important and essential improvements to the track fitting. A momentum resolution of 77 keV/c and angular resolution of 0.0057 in $\cos\theta$ have been achieved. Track reconstruction (but not MC generation) currently assumes a uniform magnetic field; to reduce tracking systematics, the group is working hard to switch as soon as possible to the actual field as already carefully mapped. Similarly, the group is striving to extract drift chamber space-time relations from the data themselves, including the so far neglected dependence of hit error on drift distance and track angle.

Studies of biases in the Michel parameters introduced by the pattern recognition algorithms as well as by track misreconstructions and asymmetries have begun. For this purpose, the group has shown that positron tracks passing through both the upstream and downstream tracking regions are a powerful tool.

For both data and MC events, a thick Al plate has been inserted downstream of the tracking volume to study the upstream-downstream tracking asymmetry and the simulation and reconstruction of backscattered tracks. Plans have been developed for adding "dummy" entrance region material at the downstream end to make the tracker more symmetric; their implementation hinges on the outcome of the ongoing thick-plate studies.

5.2 Simulation

The *TWIST* experiment is designed to maintain an acceptance near unity within the detector's fiducial volume. Nevertheless, subtle effects exist that must be canceled by means of a comparison to MC simulation, especially when fiducial boundaries are expanded to gain statistics and leverage on the measured Michel parameters. The group has made great strides toward the comparison of simulation to data, but, as yet, they do not consider their progress to be sufficient to demonstrate that 10^{-3} results on ρ and δ can be achieved. A central question is whether GEANT3 models sufficient physics at low energies, or whether the more sophisticated but less well tested GEANT4 is needed. Logistical considerations strongly favor basing a near-term result on GEANT3.

The group has identified a number of comparisons that can reveal simulation problems. The slight difference in the amount of Al in the upstream and downstream halves of the detector leads to visible differences in angular acceptance outside the fiducial volume, and to measurable systematic effects in fits carried out within that volume. These effects are being studied with very high priority. Currently, energy loss and stopping distributions are in agreement; the simulation of multiple Coulomb scattering is marginal and perhaps amenable to improvement.

Special attention must be paid to the choice of fiducial volume because the experiment's sensitivity depends more upon controlling systematic errors than upon accumulating statistics. To avoid bias, decisions on including data from various fiducial regions and runs must be made *a priori*. Therefore the internal consistency of results from different groups of data, though a firm requirement, cannot serve as the primary basis for such decisions.

For future analyses of Michel parameters at the 10^{-4} level, it will be necessary to revisit the question of whether the radiative corrections in the MC generator are sufficient.

5.3 Blind analysis and parameter fitting

The sensitivity of *TWIST* to Michel parameters is not encapsulated within some relatively small region of phase space. Therefore, to achieve a blind analysis, it would not be practical to hide the critical data until the analysis procedures are finalized; most of the data would need to be hidden. Instead *TWIST* MC events are generated based on a single "standard" set of Michel parameters that have been chosen at random, to which the experimenters plan to remain blind until the final result is determined. This information is sufficiently well guarded that it should be possible for group members to resist the natural temptation to unveil it.

In this blind analysis scheme, fitting of data to MC is facilitated by linearizing the decay rate in terms of deviations of the Michel parameters from the standard set. Data are fit to the sum of the MC standard spectrum and a set of distributions based on the spectrum's derivatives with respect to the parameters. Fitting a data sample against an MC sample yields fit parameters that are only the deviations ($\Delta\rho$, $\Delta\delta$, *etc.*) from the standard set of Michel parameters used in MC generation. The program that fits Michel parameters to data has passed a number of nice statistical tests, and appears to be working at a level sufficient for the experiment.

5.4 Computing resources

The computing resources available to the TWIST collaboration were described. The group has a cluster of 30 dedicated CPUs at TRIUMF and access to the WESTGRID facility at UBC. The dedicated cluster proved totally inadequate for the requirements of the TWIST group, and progress on the analysis had been delayed until the WESTGRID became available in November 2003. Gaining recent access to WESTGRID during its beta test stage has accelerated the analysis progress, yielding the bulk of the results presented. Ultimately, simulation needs will dominate the required computing resources.

An ensuing discussion focused on the adequacy for analyses at the 10^{-4} level of WESTGRID resources that it is hoped would be available to TWIST long-term. These resources represent about 5× the CPU presently available in the TRIUMF TWIST cluster. Group members assured the review committee that the hoped-for resource level should suffice, but no quantitative reconciliation of that level with TWIST's long-term computing load was presented.

6. SYSTEMATIC ERRORS

6.1 Comparison methods

To estimate the sensitivity of the measured Michel parameters to various systematic effects, samples of both real and simulated data were used. A number of effects were studied by recording large data samples with modified operational parameters (such as solenoid field and chamber HV). For other effects, MC samples were generated with modified parameters, exaggerated typically by one order of magnitude. Tables of differences of Michel parameters were exhibited for MC-to-MC, data-to-data, and data-to-MC fits, representing many such excursions. However, the experimenters have not yet finalized a strategy for using this information to define overall systematic uncertainties for the Michel parameters. In particular, the scale factors needed to calculate the actual systematic uncertainties were not reported and in many cases are not yet fully understood. Consequently the experimenters have not yet quantified the current systematic errors or ranked the importance of different error sources.

6.2. Michel parameters and systematics

Presentations on the status of the extraction of ρ, δ, and $\xi\mathcal{P}_\mu$ from the existing data were made by the three students responsible for writing Ph.D. theses based on these measurements. Following the recommendations of the previous review committee, the initial analyses are focused on measuring ρ and δ at the level of precision of 10^{-3}.

As discussed above, extensive studies have been made of the systematic errors. As examples, the presentation on ρ emphasized the uncertainties arising from event selection and track reconstruction. The δ presentation emphasized the energy calibration. As with the other studies presented, this work used MC datasets containing of order 10^7 events, a level such that uncertainties due to MC statistics were not negligible. The studies are far from final, but they do seem to indicate that the systematic errors will not be greater than a few times 10^{-3}. The statistical error on the existing datasets will be 1-2 $\times$ 10^{-3} depending on the composition of the signal dataset.

Although the group did not attempt to prove that the current data and analysis will yield a total error on ρ and δ of 10^{-3}, it did show convincing evidence that the methodology is sound, and it does expect to finalize measurements with a precision at this general order of magnitude within a few months, if it is able to devote sufficient priority to that task.

Achieving a total error on $\xi\mathcal{P}_\mu$ of 10^{-3} will require more data in light of the beam polarization issues discussed in section 3. Apart from beam polarization, this measurement is particularly sensitive to upstream-downstream detector asymmetries. As described in sections 5.1 and 5.2, this is an area of intensive current study.

This review did not include a presentation on the measurement of η.

7. DISCUSSION

The December 2001 TWIST site visit report "*strongly encourages the collaboration to focus their attention on the determination of ρ and δ to 10^{-3} during 2002.*" The January 2003 site visit report expects "*2003 will see a publication of ρ and δ at 10^{-3}...*" Nevertheless, at this January 2004 review, TWIST neither reported a result for ρ or δ, nor attempted to demonstrate that a 10^{-3} error on those parameters is within present reach.

At the very least, relative to the expectations of earlier review committees and of the experimenters themselves, progress toward a 10^{-3} result for ρ and δ has been delayed. What accounts for the delay?

TWIST has suffered tragedies along with its share of setbacks. Two key members of the team, including the spokesman, suddenly and unexpectedly passed away. Eight weeks of 2002 beam time were lost to a solenoid quench. To reduce bias in track reconstruction, added instrumentation was needed for the wires in the outer eight drift chamber planes. A mylar target was found to depolarize stopped muons and had to be replaced with pure Al. The solenoid fringe field near the muon entrance region had to be remapped. For illuminating the M13 beam, the use of a 2 mm carbon target turned out not to be compatible with TWIST running; substitution of a larger water-cooled target inflated the beam emittance. Only in November 2003 did the WESTGRID computing facility become available.

The committee's impression is that the TWIST leadership now headed by Glen Marshall has capably navigated these shoals and maintained the group's focus on objectives consistent with prior review recommendations.

Notwithstanding these setbacks, the committee believes that the primary source of delay in producing a 10^{-3} measurement of ρ and δ has been the great effort required to build a suite of analysis software that is sophisticated enough to allow systematic errors to be controlled at the desired level. When planned upgrades are completed, the TWIST track reconstruction, fitting, and simulation software will be much more complex than that used by earlier measurements of muon decay parameters. However, the TWIST developers, including a handful of excellent graduate students and postdocs, comprise a relatively small group.

The committee has seen no evidence that TWIST's delay in producing a 10^{-3} publication has resulted from encountering one or more obstacles to a measurement at that level which cannot reasonably be surmounted.

8. RECOMMENDATIONS

8.1 Response to charge

This committee was asked "to determine whether sufficient progress has been made identifying systematic effects and how to address them, on the way to measuring ρ and δ to 10^{-3}, that measuring the [muon decay] parameters to a precision of 3×10^{-4} is still feasible for the experiment."

We agree with prior reviewers that a publication at the 10^{-3} level is an essential milestone on the way to 3×10^{-4}. Lacking any result, neither can we assert that the 3×10^{-4} level is within *TWIST*'s reach, nor can we identify a show-stopper.

8.2 Recommendation

The committee recommends that a manuscript describing a measurement of ρ and δ be submitted to a refereed journal by October 1, 2004 (the time of the next grant application), regardless of the level of measurement uncertainty that it represents. We recommend that no further regular data collection be undertaken before that submission.

Discussion: An initial publication will focus group members and grant reviewers alike on the primary sources of error and on strategies for controlling them. An interval unencumbered by data accumulation (apart from brief tests) will encourage all collaborators to devote their strongest efforts to the task urgently at hand. The precision achieved in this publication and the experience gained in preparing it should allow a much clearer assessment of *TWIST*'s future prospects.

8.3 Personnel recommendation

We concur with the previous review committee that "*a strong and experienced analysis coordinator is needed to focus the team effort and drive the offline analysis.*" This role is distinct from, and complementary to, the role of spokesperson now being handled capably by Glen Marshall. During this crucial period the analysis coordinator should be devoted 100% to *TWIST*.

8.4 Further recommendations

- Planned upgrades to track reconstruction (data-derived distance *vs.* time and hit error *vs.* drift time and track angle; use of mapped magnetic field) should be expedited. Special effort should be devoted to albedo tracks, which can exacerbate upstream-downstream asymmetries important for measuring $\xi\mathcal{P}_\mu$.
- Planned simulation studies (importance of dummy endcap, modeling of albedo) should be expedited. Any GEANT3 → GEANT4 migration should be delayed until after the first publication.
- For the initial measurement of ρ and δ, the fiducial region should be chosen to optimize the total error. That choice, and the choice of datasets which define the signal sample, must be made *a priori*, and soon.
- A coherent and quantitative computing plan should be developed, reconciling the needs of analysis at the 3×10^{-4} level with the resources that are expected to be available.

Wednesday, January 14
TRIUMF Auditorium

09:00	Introduction: Summary of Progress in 2003	G. Marshall	20+10
09:30	M13 beam measurements	R. Mischke	20+10
10:00	Chamber alignment	S. Stanislaus	20+10
10:30	Coffee		
11:00	WestGrid utilization and experience	R. Poutissou	20+10
11:30	Review of software and development	A. Olin	20+10
12:00	Tracking philosophy and improvements	K. Olchanski	20+10
12:30	Lunch		
13:15	Tour of TWIST and/or *in camera* meeting		
14:00	MC fitter and blind analysis	A. Gaponenko	20+10
14:30	Systematics tests and methods to estimate uncertainties	D. Gill	20+10
15:00	Coffee		
15:30	Status of systematic comparisons	M. Quraan	20+10
16:00	Verification of GEANT3 simulations and material issues	R. MacDonald	20+10
16:30	Further questions and discussion and/or *in camera* meeting		

Thursday, January 15
TRIUMF Auditorium

09:00	Analysis of ρ, and systematics at 10^{-3}	J. Musser	20+10
09:30	Analysis of δ, and systematics at 10^{-3}	A. Gaponenko	20+10
10:00	Analysis of $\mathcal{P}_\mu\xi$, and systematics at 10^{-3}	B. Jamieson	20+10
10:30	Coffee		
11:00	Future plans and developments for improved precision	G. Marshall	20+10
11:30	Final questions and discussion		
12:30	Lunch		
13:15	Preparation of Review Report (*in camera*)		