TWIST

The TRIUMF Weak Interaction Symmetry Test

Precision Muon Decay at TRIUMF

Nathan Rodning
University of Alberta

TWIST: Universities of Alberta, British Columbia, Northern British Columbia, Montreal, Saskatchewan; TRIUMF, Texas A&M, Valporaiso, KIAE - Russia
TWIST - Personnel

TRIUMF
- Willy Andersson
- Yuri Davydov
- Jaap Doornbos
- Wayne Faszer
- Dave Gill
- Peter Gumplinger
- Richard Helmer
- Robert Henderson
- John Macdonald
- Glen Marshall
- Art Olin
- David Ottewell
- Robert Openshaw
- Jean-Michel Poutissou
- Renee Poutissou
- Grant Sheffer
- Hans-Christian Walter
- Dennis Wright

Alberta
- Andrei Gaponenko
- Peter Green
- Peter Kitching
- Rob MacDonald
- Maher Quraan
- Nathan Rodning
- John Schaapman
- Farhana Sobratee
- Jan Soukup
- Glen Stinson

British Columbia
- Blair Jamieson
- Doug Maas
- Mike Hasinoff

Northern British Columbia
- Elie Korkmaz
- Tracy Porcelli

Montreal
- Pierre Depommier

Regina
- Ted Mathie
- George Price
- Roman Tacik

Saskatchewan
- Bill Shin

Texas A&M
- Carl Gagliardi
- John Hardy
- Jim Musser
- Robert Tribble
- Maxim Vasiliev

Valparaiso
- Don Koetke
- Robert Manweiler
- Paul Nord
- Shirvel Stanislaus

KIAE (Russia)
- Arkadi Khruchinsky
- Vladimir Selivanov
- Vladimir Torokhov

Students
Professional Staff
Outline

- Background on muon decay
- The E614 Experiment
- Sensitivity to new physics
(V-A) Interaction is built in
- parity violation is perfect
- exchange particle is known

Only one coupling is non-zero in the Standard Model

\[
\begin{align*}
| g_{RR}^s | &= 0 & | g_{RR}^V | &= 0 & | g_{RR}^T | &= \text{zero} \\
| g_{LR}^s | &= 0 & | g_{LR}^V | &= 0 & | g_{LR}^T | &= 0 \\
| g_{RL}^s | &= 0 & | g_{RL}^V | &= 0 & | g_{RL}^T | &= 0 \\
| g_{LL}^s | &= 0 & | g_{LL}^V | &= 1 & | g_{LL}^T | &= \text{zero}
\end{align*}
\]
• The operator (V-A) satisfies the requirement that the Weak interaction violates parity.

• (V-A) violates parity perfectly

• The (V-A) operator projects out the left-handed (negative chirality) component of the wave function

\[ \bar{\psi} \gamma^\mu (1 - \gamma^5) \psi = \bar{\psi} \gamma^\mu (1 - \gamma^5) \begin{bmatrix} \psi^+ \\ \psi^- \end{bmatrix} \]

\[ = \bar{\psi} \gamma^\mu \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \psi^+ \\ \psi^- \end{bmatrix} = \bar{\psi} \gamma^\mu \psi^-\]

• the (V-A) theory therefore states that leptons with positive chirality do not undergo weak interactions.
A more general interaction - which does not presuppose the W

\[ \text{rate} \sim \sum_{\gamma=S,V,T} g_{\gamma}^{ij} \left| \bar{\psi}_{ei} | \Gamma^{\gamma} \psi_{V_{e}} \right| \left| \bar{\psi}_{V_{\mu}} | \Gamma^{\gamma} \psi_{\mu j} \right|^{2} \]

Allows for possible
- scalar
- vector
- tensor

interactions of right-handed and left-handed leptons
The preceding - in terms of the Michel parameters

\[
rate \sim x^2 \left[ 3 - 3x + \frac{2}{3} \rho (4x - 3) + P_\mu \xi \cos(\theta) \left( 1 - x + \frac{2}{3} \delta (4x - 3) \right) \right]
\]

For example-

\[
\rho = \frac{3}{4} \left[ |g_{LL}^V|^2 + |g_{RR}^V|^2 + |g_{LR}^T|^2 + |g_{RL}^T|^2 \right] + \frac{3}{16} \left[ |g_{LL}^S|^2 + |g_{RR}^S|^2 + |g_{LR}^S|^2 + |g_{RL}^R|^2 \right] - \frac{3}{4} \left[ \text{Re}(g_{LR}^S g_{LR}^{T*}) + \text{Re}(g_{RL}^S g_{RL}^{T*}) \right]
\]

= \frac{3}{4} \quad \text{when} \quad |g_{LL}^V|^2 = 1

and other couplings are zero

Above expression is modified by radiative corrections, required to second order

Similar expressions exist defining \( \xi \) and \( \delta \).

A fourth parameter, \( \eta \), contributes to order \( (m_e/m_\mu) \)
The Expression becomes considerably simpler in the Standard Model

\[
\text{rate} \sim x^2 \left[ 3 - 3x + \frac{2}{3} \rho(4x - 3) + P_\mu \xi \cos(\theta) \left( 1 - x + \frac{2}{3} \delta(4x - 3) \right) \right]
\]

For example-

\[
\rho = \frac{3}{4} \left[ |g_{LL}|^2 + |g_{RR}|^2 + |g_{LR}|^2 + |g_{RL}|^2 \right] \\
+ \frac{3}{16} \left[ |g_{LL}^T|^2 + |g_{RR}^T|^2 + |g_{LR}^T|^2 + |g_{RL}^T|^2 \right] \\
- \frac{3}{4} \left[ \text{Re}(g_{LR}^* g_{LR}^T) + \text{Re}(g_{RL}^* g_{RL}^T) \right]
\]

\[
= \frac{3}{4} \quad \text{when} \quad |g_{LL}|^2 = 1
\]

and other couplings are zero

Similar expressions exist defining \( \xi, \delta, \) and \( \eta. \)
This simple model may be too simple

**exchange particle:**

<table>
<thead>
<tr>
<th>spin 0</th>
<th>spin 1</th>
<th>spin 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>g_{RR}^{S}</td>
<td>&lt; 0.066$</td>
</tr>
<tr>
<td>$</td>
<td>g_{LR}^{S}</td>
<td>&lt; 0.125$</td>
</tr>
<tr>
<td>$</td>
<td>g_{RL}^{S}</td>
<td>&lt; 0.424$</td>
</tr>
<tr>
<td>$</td>
<td>g_{LL}^{S}</td>
<td>&lt; 0.55$</td>
</tr>
</tbody>
</table>

All but one of these terms has been set to zero in the Standard model for simplicity

**The Weak Interaction may not be purely (V-A)**
We propose to study $10^9 \mu^+$ decays

Goal:

• to determine the Michel parameters to a few parts in $10^4$

• to test for weak couplings inconsistent with the Standard Model
TWIST - Spectrometer

E614

Beam

Superconducting magnet and cryostat
Support cradle
Prop. & drift chambers
Target
Beam pipe
Yoke
TWIST – 1AT1 depolarization

1AT1 Scatter => ~ 0.0001 depolarization

slope = \frac{2}{10^4} depolarization per 25 \mu\text{m} depth
Planar drift chambers sample positron track
The TWIST yoke pieces were delivered and assembled before Christmas.

Alignment was completed in the first week of January.
TWIST – Solenoid and WC track

Track is in place and aligned to accept detector cradle and stack

Magnet is cooling
Commissioning begins this week
Mapping complete by end of March
TWIST Glass Planes

Planes are assembled on glass plates with optical precision relative to longitudinal coordinate.
TWIST – Chamber Support Cradle
**E614 Precision**

**Accepted Experimental Values**

\[ \rho = 0.7518 \pm 0.0026 \]

\[ P_{\mu \xi} = 1.0027 \pm 0.0085 \]

\[ \delta = 0.7486 \pm 0.0038 \]

\[ \eta = -0.007 \pm 0.013 \]

**E614 Proposal**

\[ \sigma_\rho = \pm 0.00005 \pm 0.00009 \]

\[ \sigma_{P_{\mu \xi}} = \pm 0.00010 \pm 0.00010 \]

\[ \sigma_\delta = \pm 0.00008 \pm 0.00010 \]

\[ \sigma_\eta \approx \pm 0.003 \]

25-60 fold improvement in precision on the Michel parameters

3-10 fold improvement in couplings
The (forward - backward) distribution goes flat at a value of $x$ dependant (only) upon $\delta$

$$[\text{Forward – Backward}] \sim x^2 \left[ 2P_\mu \xi \cos(\theta) \left( 1 - x + \frac{2}{3} \delta(4x - 3) \right) \right]$$

$$x^2 \left[ 2P_\mu \xi \left( 1 - x + \frac{2}{3} \delta(4x - 3) \right) \right]$$

Find $x$ such that term vanishes

Sensitive primarily to $\delta$

Standard Model
Uncertainty in $\delta$
E614 Sensitivity

NL Rodning, University of Alberta - February 2001
Same as the previous slide - on expanded scale

\[ x^2 \left[ 2P_{\mu\xi} \left( 1 - x + \frac{2}{3} \delta (4x - 3) \right) \right] \]

Zero crossing determines \( \delta \)
Slope is essentially \( P_{\mu\xi} \)

Standard Model
Uncertainty in \( \delta \)
E614 Sensitivity
Minimal extensions to the Standard Model

Allowing only vector couplings result in simplified Michel parameters

\[ \rho = \frac{3}{4} \left[ |g_{LL}|^2 + |g_{RR}|^2 + |g_{LR}|^2 + |g_{RL}|^2 \right] \]

\[ + \frac{3}{16} \left[ |g_{LL}^S|^2 + |g_{RR}^S|^2 + |g_{LR}^S|^2 + |g_{RL}^S|^2 \right] \]

\[ - \frac{3}{4} \left[ \Re(g_{LR}^S g_{LR}^{T*}) + \Re(g_{RL}^S g_{RL}^{T*}) \right] \]

In the context of the model,

Four parameters and four unknowns

\[ \xi \equiv |g_{LL}|^2 + 3 |g_{LR}|^2 - 3 |g_{RR}|^2 - |g_{RR}|^2 + 5 |g_{LR}^T|^2 \]

\[ - 5 |g_{RL}^T|^2 + \frac{1}{4} |g_{XL}^S|^2 - \frac{1}{4} |g_{XR}^S|^2 + \frac{1}{4} |g_{XR}^S|^2 - \frac{1}{4} |g_{XR}^S|^2 \]

\[ + 4 \Re(g_{LR}^S g_{LR}^{T*}) - 4 \Re(g_{RL}^S g_{RL}^{T*}) \]

\[ \eta \equiv \frac{1}{2} \Re\left( \frac{g_{LL}^V g_{SR}^X + g_{RR}^V g_{XR}^X}{g_{SR}^X + g_{XR}^X} \right) \]

\[ + \frac{1}{2} \Re\left( g_{RL}^V \left( g_{SR}^{T*} + 6 g_{SLR}^{T*} \right) + g_{LR}^V \left( g_{SR}^S + 6 g_{RL}^S \right) \right) \]
# Anticipated sensitivity to new couplings

<table>
<thead>
<tr>
<th></th>
<th>Current Limits</th>
<th>E614(A)</th>
<th>E614(B)</th>
<th>E614(C)</th>
<th>E614(D)</th>
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<tbody>
<tr>
<td>$</td>
<td>g^S_{RR}</td>
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<td>&lt;0.066</td>
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<tr>
<td>$</td>
<td>g^V_{RR}</td>
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<td>&lt;0.033</td>
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<td>g^V_{LR}</td>
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<td>&lt;0.060</td>
<td>0.012</td>
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<td>&lt;0.036</td>
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<td>—</td>
</tr>
<tr>
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<td>g^V_{RL}</td>
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<td>&lt;0.110</td>
<td>0.012</td>
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</tr>
<tr>
<td>$</td>
<td>g^T_{RL}</td>
<td>$</td>
<td>&lt;0.122</td>
<td>—</td>
<td>0.008</td>
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<tr>
<td>$</td>
<td>g^S_{LL}</td>
<td>$</td>
<td>&lt;0.55</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$</td>
<td>g^V_{LL}</td>
<td>$</td>
<td>&gt;0.96</td>
<td>&gt;0.99977</td>
<td>&gt;0.9993</td>
</tr>
</tbody>
</table>

Upper limits (90% CL) for weak coupling constants with current limits taken from the Particle Data Group. Improved limits expected from TWIST based on measurements of $\rho$, $\xi$, $\delta$ and $\eta$ 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.
Assume manifest L-R Symmetry

\[ g_R = g_L \]

\[ \text{CKM}_R = \text{CKM}_L \]

and no CP violation

Beta decay, \( p\bar{p} \) direct production, and muon decay are complimentary
E614 Timeline

- High Priority at TRIUMF – 1993
- First Capital Funding – April 1997
- WC Review - January 1999
- Mechanical Review - June 1999
- Beam Tests - final prototype - August 1999
- Full WC Production underway - March 2000
- WC Module Completion May 2000 – April 2001
- WC Bench tests beginning June 2000
- Yoke assembly December 2000
  - Yoke, Solenoid, and cryogenics Commissioning: February - April 2001
  - First beam: Summer of 2001
  - Preliminary Physics: December 2002
Spectrometer Resolution

- **Efficiency**
  - Plots for Plane 4 and Plane 5 showing efficiency versus wire number.

- **Residuals RMS**
  - Graph showing residuals RMS (in µm) versus drift radius (in cm).

- **Angular resolution**
  - Comparison of baseline and Mod1 angular resolution with HWHM (cosθ).

- **Momentum resolution**
  - Plot of HWHM (MeV/c) versus θ for baseline and Mod1.
Quality Control on stringing of Wire Planes

The figures show:

1. Wire-to-wire variation in $z$ position for a typical plane; $\sigma = 2.6 \, \mu$

2. Average error in wire position over 25 drift planes; $\sigma = 2.58 \, \mu$

3. Average wire tension over 38 drift planes; rms = 0.94g
TWIST Requires

- 240 preamplifiers
- 268 postamplifiers
- 42 TDC’s

Status

- 86 preamplifiers tested, 41 in mid-production
- 120 postamplifiers tested, 180 more in production
- 47 TDC’s in hand

Cross talk is minimal (0.8% amplitude), and is easily rejected in software by cutting on pulse width.
Beamline studies from October/November 2000

- Backgrounds
  - Rates: $e^+/\mu^+ \sim 4$
    (as expected)

A pyrolytic graphite target will give us a 33% improvement in the rate relative to the positrons
TWIST — RF Cuts

Flight time through beamline

Surface Muons gated on cyclotron RF

Time characteristic of $\pi$ decay

Backgrounds (extrapolated from higher momentum)

Cloud Muons

Rate: 9% that of surface muons

NL Rodning, University of Alberta - February 2001
TWIST – Cloud muon polarization

Surface muons

Polarization of the cloud muons is approximately 0.30 (opposite to the surface muon polarization of −1.0)

Cloud muon flux is 9% that of the surface muons

(Rob MacDonald – MSc data)
Flight time through beamline

By selecting a data sample with an appropriate RF gate, we can select an unpolarized sample of muons.
The edge of the distribution is used to calibrate the energy scale at large $x$.

The polarized distribution has no edge at forward angles.

The unpolarized distribution will be used to calibrate the energy scale at all angles.

52.8 MeV
Endpoint energy calibrations can be done to a precision of approximately 2 keV (where ~10 keV is needed).

Unpolarized beam will be used to provide energy calibrations independent of angle.
TWIST – 1AT1 modifications

The surface muon beam is produced in part on the surface at which the protons enter, and in part along the length of the target cylinder.

A shorter target would reduce the size of the beam spot.

A hidden proton entry point would reduce sensitivity to wander in the proton beam.

1AT1 target as imaged by M13

Surface muons
TWIST – Modified target

- Pyrolytic graphite
- Heat sink
- Cooling water supply + return

- Side view of target
- View from channel looking towards target
## TWIST - Goals

<table>
<thead>
<tr>
<th>Year</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 2001</td>
<td>Commissioning data. Preliminary alignments and calibrations</td>
</tr>
<tr>
<td>End of 2001</td>
<td>Michel distributions on tape suitable for preliminary determination of $\rho$ and $\delta$</td>
</tr>
<tr>
<td>2002</td>
<td>Installation of the TEC, Modified production target, Beamline improvements, including realignments, Improved Michel distributions based upon experience with alignments and calibrations, Field alignment studies</td>
</tr>
<tr>
<td>2003</td>
<td>Studies of depolarization in the stopping target, Preliminary $P_{\mu\xi}$ data, Precision measurements of $\rho$, $\delta$ and $\eta$</td>
</tr>
</tbody>
</table>
Δp/p of 1% selects muons from within about 20 microns of the surface.

These muons have limited multiple scattering, and little depolarization.
Secondary beams at TRIUMF

\( \mu \) polarization due to 2-body decay

Back to back to conserve linear momentum

The \( \pi \) has zero angular momentum

\( \Rightarrow \) no angular momentum in the final system

\( \mu \) selected from the surface of the production target suffer little multiple scattering

Channel resolution \( \sim 1\% \) allows selection of \( \mu \) produced within 25 microns of target surface

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Planar chambers give us a simple dependence of energy loss on $1/\cos(\theta)$.

Each successive curve is the result of a track fit using only four successive chambers.

The difference between successive curves demonstrates the small incremental energy loss per plane of $\sim 10$ keV at 0 degrees.

Fig. 9. Mean reconstructed positron energy $\overline{E_{fit}}$ as a function of $1/\cos \theta$. $E_0=50$ MeV, $\sigma_{PDG}=50$ μm. Straight lines are the fits with function $E_{fit} = E_0 - \alpha/\cos \theta$. 
These diagrams have recently been calculated by Czarnecki and Arbusov (Alberta)
Happy physicist with magnet in hand
TWIST – Event Display
The TEC has been part of our planning since June 1998
Installation planned for Spring 2002

Figure taken from detector review document, January 1999
Effective Depolarization vs. TEC Tracking Angle

Correlation relies upon a highly convergent tune, focused at the peak in the radial fringe field.
TWIST – Proton Beam Monitor

Proton Beam Monitor

- Beam Current on Plate (µA)

- Vertical Scale TW#60 (dac)

- Oct 25, 2000
  - π+ mode
  - gives 20 dac/mm
  - Down Plate
  - Top Plate

- Horizontal Scale TW#61 (dac)

- Left Plate
  - gives 133 dac/mm
  - Right Plate
Signal ratios in the target PC’s can be used to monitor the stopping distribution.
TWIST – Field Calculations

Anticipated field uniformity to 1 part in $10^4$

¼ yoke and all coils shown
- steel
- volume of reduced potential
- coils

cryogenic hole

cable slot

Dennis Wright
with OPERA-3d

NL Rodning, University of Alberta - February 2001
Unpolarized distribution in $x$

\[ [\text{Forward} + \text{Backward}] \propto 2x^2 \left( 3(1-x) + \frac{2}{3} \rho (4x - 3) \right) \]

Sensitive to shape effects at 0.4% level
Michel Parameters - defined

\[ \rho \equiv \frac{3}{4} \left[ |g_{LL}^V|^2 + |g_{RR}^V|^2 + |g_{LR}^T|^2 + |g_{RL}^T|^2 \right] \]
\[ + \frac{3}{16} \left[ |g_{LL}^S|^2 + |g_{RR}^S|^2 + |g_{LR}^S|^2 + |g_{RL}^S|^2 \right] \]
\[ - \frac{3}{4} \left[ \text{Re}(g_{LR}^S g_{LR}^{T^*}) + \text{Re}(g_{RL}^S g_{RL}^{T^*}) \right] \]

\[ \xi \equiv |g_{LL}^V|^2 + 3 |g_{LR}^V|^2 - 3 |g_{RL}^V|^2 - |g_{RR}^V|^2 + 5 |g_{LR}^T|^2 \]
\[ - 5 |g_{RL}^T|^2 + \frac{1}{4} |g_{LL}^S|^2 - \frac{1}{4} |g_{RR}^S|^2 - \frac{1}{4} |g_{LR}^S|^2 + \frac{1}{4} |g_{RL}^S|^2 - \frac{1}{4} |g_{RR}^S|^2 \]
\[ + 4 \text{Re}(g_{LR}^S g_{LR}^{T^*}) - 4 \text{Re}(g_{RL}^S g_{RL}^{T^*}) \]

\[ \xi\delta \equiv \frac{3}{4} \left[ |g_{LL}^V|^2 - |g_{RR}^V|^2 - |g_{LR}^T|^2 + |g_{RL}^T|^2 \right] \]
\[ + \frac{3}{16} \left[ |g_{LL}^S|^2 - |g_{RR}^S|^2 - |g_{LR}^S|^2 + |g_{RL}^S|^2 \right] \]
\[ - \frac{3}{4} \left[ \text{Re}(g_{LR}^S g_{LR}^{T^*}) - \text{Re}(g_{RL}^S g_{RL}^{T^*}) \right] \]