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A Precision Measurement of Muon Decay

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The $(V-A)$ structure of the weak interaction was put into the standard model by hand in order to obtain agreement with experiments. These experiments, however, do not rule out relatively large deviations from this structure. Muon decay provides an ideal laboratory to test this structure, being a purely leptonic process. The TRIUMF Weak Interaction Symmetry Test (TWIST) will measure both the energy and emission-angle distribution of positrons from the decay of polarized muons. This will provide a simultaneous determination of the Michel parameters $P_\mu \xi$, ρ and δ describing muon decay with a precision of a few parts in 10^4. Stringent limits may then be placed on the coupling constants, as well as the mass and mixing angle of a possible right-handed W boson (W_R). In this paper the formalism for muon decay is presented, TWIST is described, and the expected results are discussed.

1. Describing Muon Decay

In the charged-current sector of the standard model, only vector coupling of left-handed to left-handed fermions is allowed. A more general expression may be obtained by allowing scalar, vector, and tensor couplings of any combination of left-handed and right-handed fermions. In this case an expression for the energy and angular distribution of muon decay would take the form

$$\frac{d^2\Gamma}{dx\ d(\cos\theta)} = \Big| \sum_{\substack{i=L,R \\ j=L,R \\ \gamma=T,V,S}} g^{\gamma}_{ij} < \overline{\psi_{e_i}} | \Gamma^{\gamma} | \psi_{\nu_e} >< \overline{\psi_{\nu_\mu}} | \Gamma_{\gamma} | \psi_{\mu_j} > \Big|^2 \ , \tag{1}$$

where x is the positron's reduced energy $(x = E_{e^+}/E_{max})$ and θ is its emission angle relative to the muon polarization direction. The Γ interaction matrices are combinations of the Dirac γ matrices given by

$$\Gamma^S = 1, \quad \Gamma^V = \gamma^\mu, \quad \Gamma^T = \frac{1}{\sqrt{2}}\sigma^{\mu\nu} \equiv \frac{i}{2\sqrt{2}}\left(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu\right) . \tag{2}$$

This expression gives a set of 10 different coupling constants: g^S_{LL}, g^S_{RR}, g^S_{LR}, g^S_{RL}, g^V_{LL}, g^V_{RR}, g^V_{LR}, g^V_{RL}, g^T_{LR}, and g^T_{RL}. In the standard model, all of these coupling constants are set to zero by hand, except for g^V_{LL} which is set to one.

In order to simplify the expansion of equation 1, one can define a set of parameters (often referred to as the Michel parameters) ρ, δ, ξ, and η in terms of the coupling constants (see for example reference 1). The above standard model assumptions on the coupling constants translate into precise values for the Michel parameters so that

$$\rho = \frac{3}{4}, \quad \delta = \frac{3}{4}, \quad \xi = 1, \quad \text{and} \quad \eta = 0 , \tag{3}$$

therefore predicting a specific shape for the muon decay distribution of equation 1. A measurement of this distribution allows a comparison with the standard model.

2. The TWIST Experiment

TWIST will utilize a proton beam provided by the TRIUMF cyclotron. A pion production target intersects the beam. Pions stopping inside the target decay into muons which are 100% polarized according to the standard model. Accepting only muons produced within approximately 15 μm from the target surface, by limiting the momentum acceptance, ensures that the μ^+ polarization is not degraded by more than 1 part in 10^4 as the muons leave the target.

The highly polarized surface muon beam is stopped in the center of a highly symmetric detector, consisting mainly of 44 high precision planar drift chambers, and sitting in a nearly uniform 2 tesla solenoidal magnetic field, as shown in figure 1. This will allow, for the first time, the simultaneous extraction of all the Michel parameters from observation of a large part of the muon decay distribution. Having the statistical uncertainties at the same level as the systematic uncertainties requires the study of 10^9 μ^+ decays. These data will be acquired in approximately one month.

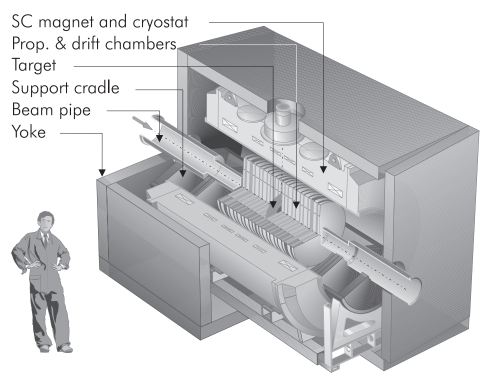

Fig. 1. The TWIST Spectrometer.

TWIST will reduce the uncertainty in the Michel parameters ρ, δ, and $P_\mu \xi$ by over one order of magnitude. While estimates for the precision of η are still uncertain, it is expected that TWIST will improve it by about a factor of 2. This will translate to improving the precision of the weak coupling constants, g^{γ}_{ij}, by a factor somewhere between 3 and 10 depending on the particular coupling and the specific assumption on the nature of the interaction. These results will also allow for improved limits on the mass and mixing angle of a possible right-handed W boson, pushing the lower limit on the W_R mass to about 800 GeV/c^2 for all mixing angles, while limiting the mixing angle to less than 0.01 over a significant range of higher W_R masses. The TWIST collaboration will perform its first engineering run in November 2000, and will begin data taking in April 2001.

1. W. Fetscher and H.-J. Gerber, *Phys. Rev.* D54, 251 (1996).