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. TRIUMF experiment E614 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, the E614 experiment is described, and the sensitivity expected from E614 is compared to present limits on the values of the coupling constants and the mass and mixing angle of W_R.

1. Describing Muon Decay

It is commonly believed among physicists that the standard model does not provide a comprehensive theory of the universe. Among several of its shortcomings are the lack of unification of all interactions, some 20 arbitrary parameters that are put into the theory by hand, its failure to explain the family hierarchy, and its failure to explain the left-right asymmetry.

For 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

$$\frac{d^2\Gamma}{dx\ d(\cos\theta)} = |\sum_{\substack{i=left,right\\ j=left,right\\ \gamma=Tensor,Vector,Scaler}} g^{\gamma}_{ij} < \overline{\psi_{e_i}}|\Gamma^{\gamma}|\psi_{\nu_e} >< \overline{\psi_{\nu_\mu}}|\Gamma_{\gamma}|\psi_{\mu_j} > |^2 \ , \tag{1}$$

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

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

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 (known 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 Experiment

The E614 experiment 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 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 they leave the target.

The highly polarized surface muon beam is stopped in the center of a highly symmetric detector, consisting mainly of high precision planar drift chambers, and sitting in a nearly uniform 2-T 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 ($x > 0.4$, $10^0 < \theta < 70^0$). Having the statistical uncertainties at the same level as the systematic uncertainties requires the study of 10^9 μ^+ decays. This data will be acquired in approximately one month.

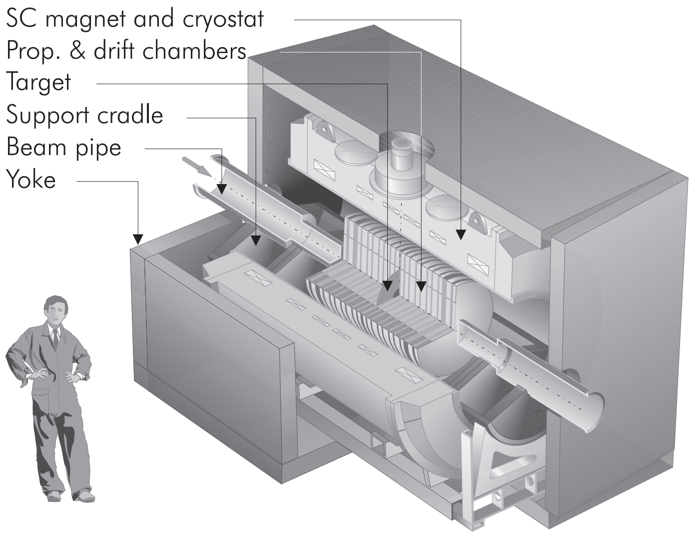

Figure 1. The E614 Spectrometer.

3. E614 Sensitivity

E614 will reduce the uncertainty by over one order of magnitude in the Michel parameters ρ, δ, and $P_\mu\xi$. While estimates for the precision of η are still uncertain, it is expected that E614 will improve it by about a factor of 2. Table 1 shows how these limits translate into limits on the coupling constants under different assumptions. In general, E614 will improve the precision of these coupling constants by somewhere between a factor of 3-10 depending on the particular coupling and the specific assumption on the nature of the interaction.

These results will also allow us to improve the present limits on the mass and mixing angle of a possible right-handed W boson. Figure 2 is an exclusion plot summarizing the current experimental limits and those expected from E614.

4. Current Status

The E614 experiment is currently under preparation at TRIUMF. Tests have been performed on the prototype chambers, resulting in the desired precision and efficiency. The mass production of the 28 XY chamber pairs has started. The 2-T superconducting solenoid has been purchased and is in the process of being mapped. The collaboration is expecting to start taking data with the full chamber in January 2001.

REFERENCES

1. W. Fetscher and H.-J. Gerber, Phys. Rev. D54, 251 (1996).
2. A. Jodidio et al., Phys. Rev. D37, 237 (1988); Phys. Rev. D34, 1967 (1986).
3. S. Abachi et al. (D0 collaboration), Phys. Rev. Lett. 76, 3271(1996).

	Standard Model	Current Limits	E614(A)	(B)	(C)	(D)
$\lvert g^S_{RR}\rvert$	0	<0.066	—	—	0.034	0.045
$\lvert g^V_{RR}\rvert$	0	<0.033	0.012	0.017	0.017	0.022
$\lvert g^S_{LR}\rvert$	0	<0.125	—	—	0.034	0.046
$\lvert g^V_{LR}\rvert$	0	<0.060	0.012	0.015	0.015	0.018
$\lvert g^T_{LR}\rvert$	0	<0.036	—	0.010	—	0.013
$\lvert g^S_{RL}\rvert$	0	<0.424	—	—	—	—
$\lvert g^V_{RL}\rvert$	0	<0.110	0.012	0.012	0.012	—
$\lvert g^T_{RL}\rvert$	0	<0.122	—	0.008	—	—
$\lvert g^S_{LL}\rvert$	0	<0.55	—	—	—	—
$\lvert g^V_{LL}\rvert$	1	>0.96	>0.99977	>0.99942	—	—

Table 1
Standard Model values and experimental upper limits (90% CL) for weak coupling constants with current limits taken from Fetscher and Gerber [1]. Improved limits set by E614 based on our measurements of ρ, ξ, and δ 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. For case (C), our measurement of η will also set a more stringent limit than above on the real (CP-conserving) part of g^S_{RR}.

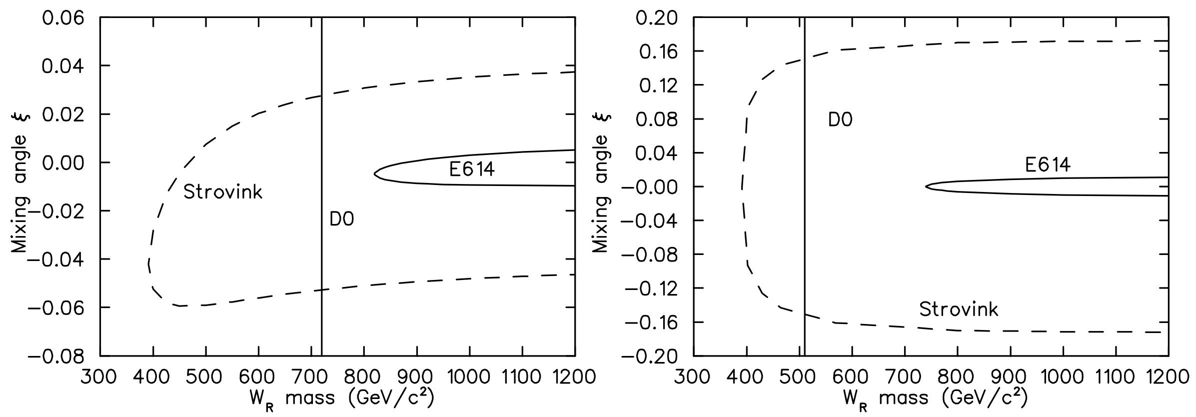

Figure 2. Current and proposed 95% CL limits on W_R mass vs. mixing angle. The curves in the left figure are calculated assuming that the left- and the right-handed CKM matrices are identical. The curves in the right figure make no assumptions on the right-handed CKM matrix. Solid vertical line: W_R mass limit from D0[3]. Solid curve: allowed region from E614 under the same assumptions. Dashed curve: allowed region from Jodidio et al.[2]