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Search for Right-Handed Currents by Means of Muon Spin Rotation

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A \( \mu \)SR technique has been used to place limits on right-handed currents in \( \mu^+ \) decay. The spins of polarized \( \mu^+ \) stopped in metal targets were precessed by 70-G or 110-G transverse fields. The \( \mu \)SR signal amplitude produced by high momentum decay \( e^+ \) emitted near the beam direction implies \( \xi P_\mu \xi/\rho > 0.9955 \) and \( M(W_2) > 370 \) GeV (90% confidence), where \( W_2 \) is a predominantly right-handed gauge boson. The present result combined with our previous spin-held analysis yields \( \xi P_\mu \xi/\rho > 0.9966 \) and \( M(W_2) > 400 \) GeV.

In \( SU(2)_L \times SU(2)_R \times U(1) \) left-right symmetric electroweak models\(^1\) the charged gauge boson weak eigenstates \( (W_L, W_R) \) and mass eigenstates \( (W_1, W_2) \), are related by \( W_1 = W_L \cos \xi - W_R \sin \xi, \) \( W_2 = W_L \sin \xi + W_R \cos \xi \). Stringent limits on the mixing angle \( \xi \) and the square of the mass ratio \( \alpha = M^2(W_1)/M^2(W_2) \) are obtained from muon decay provided any \( \nu_R \) that couples to \( W_R \) has negligible mass. We have previously reported\(^2\) the 90% confidence limits \( M(W_2) > 380 \) GeV and \( |\xi| < 0.045 \) for infinite \( W_2 \) mass from an analysis of the \( e^+ \) momentum spectrum near the endpoint opposite
to the $\pi^+$ spin, where the $V-A$ rate vanishes. Further constraints\(^2\) are placed by the muon decay Michel parameter $\rho$\(^3\) and by the $^{19}$Ne asymmetry $A(0)$\(^4\) and $\Gamma$ value\(^5\) assuming CVC. The $\gamma$ distributions in $vN$ and $\bar{v}N$ scattering constrain\(^6\) $|\xi|(1-\alpha)<0.095$ irrespective of the $\nu_R$ mass. Model dependent limits, independent of the $\nu_R$ mass but assuming the same left- and right-handed quark mixing angles, are set by semileptonic decays\(^7\) $|\xi|(1-\alpha)<0.005$, current algebra analysis of non-leptonic $\Delta S=1$ weak decays\(^8\) $|\xi|(1-\alpha)<0.004$, and $M(W_Z)>300$ GeV if $\xi=0$, and the $K_L-K_S$ mass difference\(^9,10\) $[M(W_Z)>1.6\,\text{TeV}]$. Here we present additional limits from $\mu^+$ decay based on a precise measurement of the decay $e^+$ spectrum asymmetry above 46 MeV/c using a muon spin rotation ($\mu$SR) technique.

The $\mu$SR data in Fig. 1 reflect the stopped $\mu^+$ decay rate, relative to that for unpolarized muons,

$$R(\bar{x},\theta) = 1 \times \frac{1-2\bar{x}}{1+2\bar{x}} P_\mu A(\bar{x}) \cos \theta(t)$$

where $\theta(t)$ is the angle between the direction of $\mu^+$ polarization $P_\mu$ and the $e^+$ momentum direction $\hat{P}_e$, $\bar{x} = 1-x = 1-P_e/P_{e\text{e}(\text{max})}$, and $A(\bar{x})=\pm 1$ in the $V-A$ limits. [Finite electron mass and radiative corrections\(^11\) omitted from Eq. (1) are included in the analysis.] With the muon-decay parameters\(^11\) $\xi, \delta$, and $\rho$

$$A(\bar{x}) = (\xi \delta / \rho) [1 + 2 \bar{x} (\frac{\delta}{1-2\bar{x}} - \frac{3\bar{\rho}}{1+2\bar{x}})]$$

where $\delta=1-4\xi/3$ and $\bar{\rho}=1-4\rho/3$. In left-right symmetric theories\(^12\)

$P_\mu = 1-2(\alpha+\xi)^2$ along $\hat{P}_\mu$ for $\mu^+$ from $\pi^+$ decay at rest. Normalized to that for $V-A$ decay of $\mu^+$ with $P_\mu = 1$, the $\mu$SR signal amplitude is $P_\mu A(\bar{x})$, and the endpoint amplitude $P_\mu A(0) = \xi P_\mu \delta / \rho = 1-2(2\alpha^2+2\alpha\xi+\xi^2)$ restricts $\alpha$ and $\xi$.

The TRIUMF M13 beamline\(^13\) produced an almost completely polarized
29.5 MeV/c beam of 15,000 $\mu^+$/sec within a 1% $\Delta p/p$ from $\pi^+$ decay at rest near the surface of the production target. A 2% admixture of prompt $\mu^+$ from $\pi^+$ decay in flight was rejected by timing cuts with respect to the cyclotron rf cycle. The $\mu^+$ beam entered the same apparatus that we have already described in detail, and came to rest in foils of $\geq$ 99.99% pure Al, Cu, Ag, and Au, or in liquid He. The $\mu$SR data were interleaved in hourly runs with spin-held data that formed the basis of our previously published analysis. For $\mu$SR runs, the spin-holding longitudinal field ($B_L$) at the target was nulled to within ± 2-G and instead a 70-G or 110-G transverse field ($B_T$) was applied. Decay $e^+$ emitted near the beam direction were focussed by a downstream solenoid into a cylindrical dipole spectrometer for momentum analysis. The stopped $\mu^+$ and delayed $e^+$ provided the same trigger signature as described before. Here we present data from $3.7 \times 10^7$ triggers accumulated in three running periods spread over two years. Events with an extra beam particle arriving within ±10 $\mu$sec of the $\mu^+$ stop were rejected, as were events with reconstructed $\mu^+-e^+$ track separation $>0.45$ cm at the target, or polar angles $\cos\theta_{\mu}<0.99$ or $\cos\theta_e<0.975$. Additional cuts have been described previously.

As before, the decay $e^+$ momentum was obtained to first order from the sum of the horizontal coordinates at the conjugate foci of the spectrometer and its 1.07%/cm momentum dispersion. Empirical corrections, based on the $\mu$SR data endpoint, were made for deviation from the median plane and according to impact parameter with respect to the magnet axis. The resulting momentum resolution is better than 0.2% rms. The spectrometer momentum scale was calibrated with $e^+$ beams obtained at several settings of the NMR-monitored beamline elements. A consistent independent calibration was determined from the $\mu$SR data.
endpoint positions in runs using different spectrometer settings. Events with \( x < 0.88 \), having lower statistical power and larger uncertainties in \( x \), were rejected. After all cuts 5.6% of the \( \muSR \) raw triggers were retained.

The \( \muSR \) data in six 0.02 wide \( x \) bins are fitted to

\[
N(t) = N_0 \left[ \int C(x)dx + \int \mu A(\bar{x})G(t)<\cos\theta>_t \int D(x)dx \right] \exp(-t/\tau_\mu) \tag{3}
\]

We have checked that both the \( \muSR \) and spin-held data are consistent with zero background. The fitted \( \mu^+ \) mean life \( \tau_\mu = 2.209 \pm 0.006 \) (stat.) \( \mu\sec \), spin rotation frequency, and spin relaxation function \( G(t) \) representing the decay of the \( \muSR \) signal seen in Fig. 1. are common to all \( x \) bins. \( C(x) \) and \( D(x) \) are the angle independent and dependent parts respectively of the radiatively corrected V-A differential decay rate, smeared by the \( e^+ \) energy-loss straggling and by a sum of Gaussian momentum resolution functions. Momentum acceptance corrections are made to \( C(x) \) and \( D(x) \) based on the measured and expected \( \langle p_e \rangle \) within each \( x \) bin. The angular acceptance of the apparatus for decay \( e^+ \) is given by the \( \hat{p}_e \) distribution observed in time-averaged isotropic \( \muSR \) data. The corresponding parent \( \mu^+ \) polarization directions \( \hat{p}_\mu \), initially along \( -\hat{p}_\mu \), precess with frequency \( \omega = eB_T/m_\mu c \). With \( \omega \) free in the fit, these \( \hat{p}_e \) and precessing \( \hat{p}_\mu \) distributions yield the \( <\cos\theta>_t \) appropriate to each 0.04 \( \mu\sec \) time bin.

The decay of the \( \muSR \) signal in Fig. 1 is due to loss of phase coherence between the precessing \( \mu^+ \) spins. Fitting \( \mu A(\bar{x})G(t) \) to each spin precession cycle indicates approximately Gaussian spin relaxation functions \( G(t) \), as shown in Fig. 2. The fitted initial depolarization (12.4\( \pm \)0.9%) in liquid He may be due to \( \mu^+ - e^- \) spin exchange processes during \( \mu^+ \) thermalization. In metals the high free electron
concentration screens the $\mu^+$ from interactions with individual electrons, but the $\mu^+$ spins can be dephased by the local fields of randomly oriented nuclear magnetic dipole moments. In ideal metals the resulting spin relaxation for mobile $\mu^+$, with mean lattice site residence time $\tau_c$, is given approximately by the Kubo-Tomita expression \[ \exp\{-2\sigma^2\tau_c^2[\exp(-t/\tau_c)-1+t/\tau_c]\} \], which reduces to Gaussian (exponential) forms for $\tau_c \to 0$ ($\tau_c \to \infty$). The $x$-averaged $P_{\mu A}(\bar{x})$ resulting from fits to Eq. (3) using the Kubo-Tomita form and its Gaussian limit for $G(t)$ are shown in Fig. 3. We conservatively adopt the smaller $P_{\mu A}(\bar{x})$ fitted with the Gaussian form.

The second run Cu target data exhibits significantly (4.7σ) smaller $P_{\mu A}(\bar{x})$ than the other metal target data. Muon range-straggling calculations show that the 160 mg/cm$^2$ Cu target was too thin to stop the $\mu^+$ well within the target, while the 220 mg/cm$^2$ Cu target, composed of two foils, suffered from $\mu^+$ stopping between the foils. (In the first run the $\mu^+$ stopped 0.5 rms straggling lengths deeper in the second foil due to less upstream material). We base our result on the other ten statistically consistent ($\chi^2 = 7.7$) metal target data sets in Fig. 3. The target-averaged $P_{\mu A}(\bar{x})$ for each $x$ bin are shown in Fig. 4, the line being a fit to Eq. (2) using the world average values $^{15}$ of $\delta$ and $\rho$. The endpoint amplitude $P_{\mu A}(0) = \xi P_{\mu} \delta / \rho$ is thereby determined with a statistical error of $\pm 0.0016$.

Corrections totaling $+0.0016 \pm 0.0006$ are applied to the fitted $\xi P_{\mu} \delta / \rho$ for $\mu^+$ depolarization by Coulomb scattering upstream of the target and $e^+$ scattering in the target evaluated by Monte Carlo studies, and for any incomplete nulling of $B_L$. Table 1 summarizes the major systematic errors, which add in quadrature to $\pm 0.0016$. No correction is made for unknown sources of $\mu^+$ depolarization in the stopping process. Since
such effects, or any neglected background, can only decrease the apparent result we quote the limit $\xi P_{\mu6}/\rho > 0.9955$ (90% confidence). Our conservative use of the Gaussian spin relaxation form further strengthens this limit. The result implies $M(W_1) > 370$ GeV for any mixing angle $\xi$; $M(W_2) > 440$ GeV for $\xi = 0$; and $|\xi| < 0.047$ for infinite $W_2$ mass.

The good agreement between the present $\mu$SR result and the previous endpoint rate analysis result (\(\xi P_{\mu6}/\rho > 0.9959\)), despite differences in the major sources of possible systematic error, reinforces our confidence in each of them. Combining the two results sets the 90% confidence limits $\xi P_{\mu6}/\rho > 0.9966$; $M(W_1) > 400$ GeV for any $\xi$; $M(W_2) > 475$ GeV for $\xi = 0$, and $|\xi| < 0.041$ for infinite $W_2$ mass.

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<table>
<thead>
<tr>
<th>Source of Systematic Error</th>
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<tr>
<td>Coulomb scattering of $\mu^+$</td>
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<tr>
<td>Coulomb scattering of $e^+$</td>
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</tr>
<tr>
<td>Incomplete nulling of $B_L$</td>
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<td>Definition of $x=1$</td>
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<td>Momentum scale calibration</td>
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<tr>
<td>World average $\delta$, $\rho$ values</td>
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<tr>
<td>Reconstruction of $\theta_{\mu}$ and $\theta_{e^+}$</td>
<td>±0.0004</td>
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<tr>
<td>Energy-loss straggling of $e^+$</td>
<td>±0.0003</td>
</tr>
<tr>
<td>Fitted $\mu^+$ mean life $\tau_{\mu}$</td>
<td>±0.0003</td>
</tr>
</tbody>
</table>
References

(a) Present address: Department of Physics, University of Colorado, Boulder, Colorado 80309

(b) Deceased


3 The primary input to the world average is J. Peoples, Nevis Cyclotron Report No. 147 (1966).

4 D. Schreiber and F.T. Calaprice, private communication;


We used the world average values $p=0.7517\pm0.0026$, $\delta=0.7551\pm0.0085$ quoted in *Review of Particle Properties*, Rev. Mod. Phys. 56 No.2, Part II (1984), together with our preliminary new result $\delta=0.748\pm0.005$ quoted in B. Balke et al., Lawrence Berkeley Laboratory Report No. LBL-18320, yielding the combined value $\delta=0.750\pm0.004$. 
Figure Captions

FIG 1. Data from the second of three running periods, constituting 73% of the total μSR data, with (a) 70-G, and (b) 110-G transverse fields. The exponential decay with μ⁺ lifetime has been factored out.

FIG 2. Values of $P_μA(x)G(t)$ for each μ⁺ spin precession cycle with $B_T = 70$-G (circles) or 110-G (triangles). The curves assume Gaussian μ⁺ spin relaxation functions, $G(t) = \exp(-\sigma^2 t^2)$.

FIG 3. Values of $P_μA(x)$ averaged over x bins, for (a) Gaussian and (b) Kubo-Tomita forms of $G(t)$. The targets are Al (circles) 150 mg/cm² and 280 mg/cm² (marked "t"), Cu (squares) 160 mg/cm² and 220 mg/cm² (marked "t"), Ag (triangles) 270 mg/cm², and Au (inverted triangles) 240 mg/cm², with $B_T = 110$-G (open symbols) or 70-G (filled symbols). The Run 2 Cu target data are inconsistent with the average of the other data (solid line).

FIG 4. Values of $P_μA(x)$ in each x bin for metal targets, excluding run 2 Cu. Error bars are statistical errors added in quadrature to the possible systematic error from the spectrometer momentum calibration. The line is a fit to Eq. 2 using world average values of $\delta$ and $\rho$. 
FIG. 1
FIG. 3

(a) Gaussian

(b) Kubo-Tomita

RUN 1
RUN 2
RUN 3

XCG 853-185
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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