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SEARCH FOR RIGHT-HANDED CURRENTS IN MUON DECAY

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ABSTRACT

We report new limits on right-handed currents, based on precise measurement of the endpoint of the $e^+$ spectrum from $\mu^+$ decay. Highly polarized $\mu^+$ from the TRIUMF "surface" beam were stopped in pure metal foils within either an 1.1-T spin-holding longitudinal field, or a 70-gauss spin-precessing transverse field. Decay $e^+$ emitted within 200 mrad of the beam direction were momentum-analyzed to ±0.2%. For the spin-held data, decay via (V-A) currents requires the $e^+$ rate to approach zero in the beam direction at the endpoint. Measurement of this rate sets the 90% confidence limits $\xi_P \rho > 0.9959$ and $M(W_R) > 380$ GeV, where $W_R$ is the possible right-handed gauge boson. For the spin-precessed data we independently determine a 90% confidence limit $\xi_P \rho > 0.9918$.

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Within the remarkably successful Glashow-Weinberg-Salam electroweak model, spontaneously broken gauge symmetry gives the left-handed gauge boson $W_L$ a mass specified only as a function of the experimentally observed Fermi coupling strength. If the $U(1) \times SU(2)_L$ gauge group is extended e.g. to $U(1) \times SU(2)_L \times SU(2)_R$, left-right symmetry at the Lagrangian level is restored with the addition of a right-handed gauge boson $W_R$. The dominance of left-handed charged currents at present energies could then arise from a $W_L - W_R$ mass splitting which is tiny on the grand-unification scale.

In these left-right symmetric theories, the physical bosons $W_1$ and $W_2$, with mass-squared ratio $\alpha = M^2(W_1)/M^2(W_2)$, are linear combinations of the gauge bosons:

$$W_1 = W_L \cos \xi - W_R \sin \xi$$

$$W_2 = W_L \sin \xi + W_R \cos \xi$$

The effects of $W_L - W_R$ mixing and $W_2$ exchange relative to $W_1$ exchange are independent of momentum transfer well below $M^2(W_1)$. If the $\nu_R$ is light enough to be produced without significant kinematic effect, the strongest experimental limits on $\alpha$ and the mixing angle $\xi$ thus are obtained from muon and nucleon $\beta$ decay. Additional constraints are placed by model-dependent calculations of the $K_L - K_S$ mass difference and of current-algebra relations between $K \rightarrow 3\pi$ and $K \rightarrow 2\pi$ amplitudes. Present experimental bounds are displayed as contours in Fig. 1. To improve the experimental sensitivity, we have measured precisely the high-momentum region of the positron spectrum in polarized $\mu^+$ decay. This letter presents new limits set by these data, represented in Fig. 1 by the small bold ellipse.

The stopped $\mu^+$ decays of interest are those which emit $e^+$ near the momentum spectrum endpoint $x = p_e/p_{e(\text{max})} = 1$, and also near $\theta = 0$, where $x-\theta$ is the angle between $\vec{p}_e$ and the direction of $\mu^+$ polarization $P_{\mu}$. Relative to that for unpolarized muons, the decay rate is

$$R(x,\theta) = 1 - \frac{1 - 2 \xi - \frac{\beta}{2} + 4 \xi \frac{\beta}{2} }{1 + 2 \xi - \frac{\beta}{2} + 4 \xi \frac{\beta}{2} } \xi P_{\mu} \cos \theta$$

(1)
where \( x = 1 - \xi, \delta = 1 - 4\delta/3, \beta = 1 - 4\rho/3, \) and \( \xi, \delta, \) and \( \rho \) are the usual muon decay parameters.\(^{14}\) (Radiative corrections\(^{15}\) and the finite electron mass are included in the actual analysis but neglected in (1) above.) At the endpoint, \( R(1,0) = 1 - \xi P_\delta/\rho; \) and in the \( (V-A) \) limit, \( R(x=-1,\theta=0) = 6 - 4x - P_\mu \cos \theta. \) For a \( \mu^+ \) beam derived from \( \pi^+ \) decay at rest, \( \theta \) becomes the angle between the \( e^+ \) and \( \mu^+ \) momenta. Then, in left-right symmetric theories,\(^{3}\) \( P_\mu \approx 1 - 2(\alpha + \xi)^2, \) and the endpoint decay rate \( R(1,0) \approx 2(2\alpha^2 + 2\alpha^+ + \xi^2) \) constrains both \( \alpha \) and \( \xi. \)

This experiment is made possible by the nearly complete \( \mu^+ \) polarization of a beam derived from \( \pi^+ \) decay near the surface of the production target.\(^{16}\) The \( ^{\text{13}} \)C beam\(^{17} \) at the Tri-University Meson Facility (TRIUMF) cyclotron is produced by \( \pi^+ \) decay within a bare 2 mm C target at 135° to the 520-MeV proton beam direction. The 29.5-MeV/c \( \mu^+ \) are transported in vacuum through two 60° bends and are momentum-selected by slits at two intermediate foci. For collection of the present data, the beam angular acceptance was set to 20 msr, and the momentum acceptance typically to 1% FWHM, yielding 15,000 \( \mu^+ / \text{sec} \) into a 12 \( \times \) 10 mm spot. A comparable flux of beam positrons is cut out by a stopping requirement at the muon target. The 2% contamination of prompt ("cloud") \( \mu^+ \) from \( \pi^+ \) decay in flight is rejected by requiring the \( \mu^+ \) to be produced well within the 43-nsec interval between proton bursts.

Details of the muon polarimeter and its trigger are shown in Fig. 2. After passing through 25 mg/cm\(^2\) of low-Z material, beam \( \mu^+ \) are measured with an angular resolution of 20 mrad. Target foils of 99.99% pure Al, Cu, Ag, and Au were chosen for their high concentrations of free electrons. The electron sea effectively prevents the depolarization which otherwise would result from muonium formation. With the help of \textit{in situ} range measurements, the foil thicknesses (Table I) were selected to minimize \( \mu^+ \) punch-through and decay \( e^+ \) scattering. A 1.1-T longitudinal field \( (B_||) \) is also applied to preserve the stopped \( \mu^+ \) spin direction. During alternate hours the longitudinal field is nulled to within ±3 gauss and a 70-gauss transverse field \( (B_\perp) \) is substituted. This precesses the \( \mu^+ \) spin about a vertical axis so that its time-average polarization is zero. Downstream of the target, the decay \( e^+ \) is measured with an angular resolution of 10 mrad and focussed by a 0.5 T-m solenoidal field lens. The septum between the target and solenoid bore makes the focal length nearly independent of the choice of field orientation at the target.
The decay $e^+$ is momentum-analyzed by a vertical dipole magnet having approximate cylindrical symmetry, producing a central field of 0.32 T. Driftchamber systems using methane-8% methylal gas are located at its conjugate foci, and the inter:vening volume is evacuated. The dispersion $\Delta p/p$ was measured to be 1.07%/cm by passing a positron beam through the spectrometer. All dipoles are NMR-controlled. In combination, the field lens and positron spectrometer accept 250 msr within a momentum bite of $\pm 20\%$; in the analysis described below, their acceptance and momentum bite were restricted to 160 msr and $\pm 8\%$.

The trigger requires the signature of a beam particle stopping in the foil target, in delayed (0.2 - 10 $\mu$sec) coincidence with the signature of a decay positron passing through the spectrometer. The central momentum accepted by the spectrometer is set near the decay spectrum endpoint (180% of the beam momentum). When the $\mu^+$ component is removed from the beam, the raw trigger rate essentially vanishes. Events with an extra particle arriving in the target between the $\mu^+$ stop and the decay time are tagged and rejected in the analysis.

The data reported here are based upon $3.5 \times 10^6$ triggers collected during an initial three-week run in 1982. An additional $10^7$ triggers collected in late 1982 are presently being analyzed. During hourly tape changes, typically either the muon stopping foil or the field direction at the stopping point ($B_{||}$ or $B_{\perp}$) were changed; the spectrometer dipole was powered continuously. The standard TRIUMF data acquisition system logged events at rates above 100 Hz while introducing negligible deadtime; on-line analysis supplied physics as well as hardware diagnostic information, including the endpoint edge for $B_{\perp}$ data. In many special runs the beam momentum was moved above and well below the "surface edge", and other conditions were varied.

With allowance for local curvature, straight $e^+$ track segments were found separately in the horizontal and vertical projections of three groups of wire chamber planes; (P3, D1, D2); D3; and D4 (Fig. 2). All possible combinations of hits were considered and tracks in all six segments were found in 99% of the triggers. Of these, 95% had hit multiplicities which corresponded to a single incoming and outgoing track with little noise. The remainder were rejected to avoid possible confusion. Taking account of the magnetic fields, projections of track segments were required to agree at
the target, in the bore of the solenoid, and in position and vertical slope in the dipole. The trigger
counter S3 provided an additional coarse position measurement, which was required to agree with
that in D4.

Initially the nonlinear space-time relationships in the driftchambers were approximated using
uniform-illumination data. Separately for each chamber and for each run, they were dynamically
fine-tuned by minimizing residuals in the track-segment fits. Residuals of \( \leq 500 \mu \) were achieved in
P3, D1, and D2; and \( \leq 250 \mu \) in the spectrometer chambers D3 and D4. The hits found in P1
through D2 were then fitted to curved trajectories based on the first-order optics of cylindrically
symmetric fields.\(^{18}\) The \( \mu^+ \) and \( e^+ \) polar angles \( \theta_\mu \) and \( \theta_e \) with respect to the beam axis at the target
were thereby determined. Monte Carlo simulation based on higher-order field optics has verified the
accuracy of this procedure to within an uncertainty in \( \cos \theta \) of 0.0003. For the \( B_{||} \) data the
transverse component of the \( \mu^+ \) spin precesses about the beam axis too rapidly to be followed. Thus
for \( \cos \theta = \vec{P}_\mu \cdot \vec{P}_e \) in Equation(1), we substitute \( \cos \theta \cos \theta_e \), which is equivalent to an average over
many events.

The \( e^+ \) momentum was obtained by taking the sum of the horizontal coordinates at the conjunc-
tion foci of the spectrometer magnet. Using the initially fit momentum, the average square devia-
tion from the median plane, and the average impact parameter with respect to the magnet axis as
parameters, this sum was empirically corrected to second order, based on the endpoint position in
\( B_{\perp} \) data and on data from special calibration runs. The sharp edge at \( x = 1 \) in Fig. 3(a)
corresponds to a gaussian component of the positron momentum resolution which is less than 0.2%.
The slightly rounded shoulder is due primarily to Bhabha straggling in the 180 mg/cm\(^2\) of material
upstream of the spectrometer vacuum.

In addition to cuts on \( \mu^+ \) time of production, track ambiguity, and track linkage described
above, conservative fiducial cuts were applied, and events with \( x < 0.92 \) and \( \cos \theta < 0.975 \) were
dropped from the analysis. The final \( x \) distributions in Fig. 3 preserve 7.5% of the triggers. This
rate of survival is the result of loose triggering and generous acceptance, with tight cuts applied in
the analysis. For each of the important samples cut out, we have checked that any reasonable varia-
tion of the cut would negligibly affect the result. As a final check, the fitted $\mu^+$ lifetime from $B_\perp$ data is $2.205 \pm 0.010 \pm 0.040 \mu$sec, consistent with the accepted value.

The $B_\perp$ data in Fig. 3(a) are fit to the radiatively corrected spectrum expected\textsuperscript{14,15} for unpolarized $\mu^+$ decay, smeared by a sum of gaussian resolution functions and by the expected $e^+$ energy-loss straggling. The fit simultaneously calibrates the edge position $x = 1$ and determines the momentum resolution and the (quadratic) dependence of the acceptance upon $x$.

In general, the $B_{||}$ spectrum in Fig. 3(b) can be represented as the shape expected from pure $(V-A)$ with $P_\mu = \cos \theta = 1$, in linear combination with the shape of the unpolarized spectrum in Fig. 3(a). The relative contribution of this small unpolarized fraction is essentially equal to $1 - \left( \xi P_\mu \delta/\rho \right) <\cos \theta >$. To fit this fraction, we use the $B_\perp$ fit to fix the $x$ resolution and edge calibration, but allow the acceptance for $B_{||}$ data relative to that for $B_\perp$ data to vary linearly with $x$. This allows for the (<2\%) difference in angular acceptance caused by the different field configurations near the target. Using the data with partly polarized $\pi^+$ from $\pi^+$ decay in flight, we have checked that the $x = 1$ calibration is consistent for $B_{||}$ and $B_\perp$ fields. In the resulting curve in Fig. 3(b), the slight kink near $x = 1$ reflects the small fit unpolarized fraction, which arises mostly from the measured value $<\cos \theta > = 0.9862$ for these data.

The limit on $\xi P_\mu \delta/\rho$ which we report here is based on this same fitting procedure carried out for data in each of five bins in $\cos \theta$. The subdivision provides a more precise measure of $<\cos \theta >$ for each bin, and checks that the results of these fits are consistent with a linear dependence upon $<\cos \theta >$. The fit values of $\xi P_\mu \delta/\rho$ for the four target materials are in satisfactory agreement (Table I).

A correction of $+0.0012 \pm 0.0005$ has been made to all fit $\xi P_\mu \delta/\rho$, in order to account for misalignment of the $\mu^+$ spin with respect to $P_\mu$ due to Coulomb scattering upstream of the point at which $P_\mu$ is measured. Table II summarizes the major sources of systematic error. All other sources contribute $\leq 10^{-4}$. In principle the systematic errors should not be correlated; in quadrature they add to $\pm 0.0018$. We have made no correction for unknown sources of $\mu^+$ depolarization either along the beam or in the stopping target. Since such effects can only decrease the apparent result, we
therefore quote the limit

\[ \xi P, \delta / \rho > 0.9959 \ (90\% \ confidence). \]

The corresponding limits on the \( W_R \) mass and mixing parameters \( \alpha \) and \( \xi \) are represented by the small bold contour in Fig. 1. In particular, for infinite \( W_R \) mass \( |\xi| < 0.045 \) for any mixing angle \( M(W_R) > 380 \text{GeV} \); and for zero mixing angle \( M(W_R) > 450 \text{GeV} \).

The \( B_{\perp} \) data can also be used for an independent \( \mu \text{SR} \) type measurement of \( \xi P_{\mu} \). In Figure 4(a), 4(b) we show the measured time distributions of the data for all metal targets combined. The \( B_{\perp} \) data are fit to the radiatively corrected decay rate assuming V-A values for the Michel parameters \( \eta, \rho, \) and \( \delta \). We perform a simultaneous maximum likelihood fit to 125,000 \( B_{\perp} \) and 59,000 \( B_{\parallel} \) events.

For the \( B_{\parallel} \) case, the number of events is given by

\[ N_{\parallel}(t) = N_{\parallel}^0 e^{-t/\tau_{\parallel}} + BKD_{\parallel} \]

In the \( B_{\perp} \) case, the data are subdivided into four \( x \) bins, each 0.02 wide. The number of events in a given time interval, centered at \( t \), after precession by \( \rho = \omega t \), is

\[ N_{\perp}(t) = N_{\perp}^0 \left( \int A(x) dx + <\cos \theta>_{\text{bin}} \xi P_{\mu} \int B(x) dx \right) e^{-t/\tau_{\parallel}} + BKD_{\perp} \]

where

\[ <\cos \theta>_{\text{bin}} = \frac{\int_{t-dt}^{t+dt} e^{-t'/\tau_{\parallel}} dt' \left\langle \cos \theta(t' = \rho/\omega) \right\rangle}{\int_{t-dt}^{t+dt} e^{-t'/\tau_{\parallel}} dt'} \cdot R(t) \]

and the effective relaxation function is

\[ R(t) = \exp\left[ -2\sigma^2 \tau_c^2 \left( \exp(-t/\tau_c) - 1 + t/\tau_c \right) \right] \]

The thirteen fitted parameters are; \( \xi P_{\mu} \), the mean lifetime \( \tau_{\mu} \), the precession frequency \( \omega \), the relaxation parameters \( \sigma, \tau_c \), the time at the start of the of the first bin, the separate \( B_{\perp} \) and \( B_{\parallel} \)
backgrounds, and the acceptance dependent normalization for each \( x \) bin. \( A(x) \) and \( B(x) \) are calculated from equation (1). The results of the fit are shown superimposed on the \( B_\perp \) data in Figure 5. The muon lifetime dependence has been divided out. The fitted value, corrected for the effects of the small constant background term, is \( \xi P_\perp \delta/\rho = 0.9970 \pm 0.0038 \) (statistical).

Again we must correct for the upstream Coulomb scattering (\( +0.0012 \pm 0.0005 \)). For the \( B_\perp \) data there is an additional correction for the possibility of a residual longitudinal magnetic field in the target region. We estimate that the uncertainties in the field cancellation correspond to a 0.0003\( \pm 0.0003 \) correction to \( \xi P_\perp \delta/\rho \). We estimate the net systematic error to be 0.0014 and set a 90\% confidence limit \( \xi P_\perp \delta/\rho > 0.9918 \). This limit is somewhat weaker than that obtained above using the \( B_\parallel \) data but it is still considerably more accurate than the previous world average. Although it is a more complex apparatus, this type of spectrometer clearly can be used for highly sensitive \( \mu \)SR measurements.

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References


5. V.V. Akhmanov et al., Yad. Fiz. 6, 316 (1967) (Sov. J. Nucl. Phys. 6, 230 (1968)).


9. D. Schreiber and F.T. Calaprice, private communication; D. Schreiber, Ph.D. Thesis, Princeton University, 1983 (unpublished). We calculated the contour plotted in Fig. 1 using $A(0) = 0.0363 \pm 0.0008$; ft ratio $= 1.797 \pm 0.002$. See also F.T. Calaprice et al., Phys. Rev. Lett. 35, 1566 (1975).


18. K. Halbach, private communication.
TABLE I. Results of fits to $\xi P_\mu \delta/\rho$ for $\mu^+$ stopping in each of four target foils, and for the combined sample. Errors are statistical.

<table>
<thead>
<tr>
<th>Target</th>
<th>Thickness (mg/cm²)</th>
<th>$\xi P_\mu \delta/\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>154.5</td>
<td>0.9978 ±0.0028</td>
</tr>
<tr>
<td>Cu</td>
<td>233.4</td>
<td>1.0026 ±0.0026</td>
</tr>
<tr>
<td>Ag</td>
<td>275.1</td>
<td>0.9994 ±0.0036</td>
</tr>
<tr>
<td>Au</td>
<td>232.6</td>
<td>0.9970 ±0.0035</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>0.9989 ±0.0015</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Source of systematic error</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Coulomb scattering of $\mu^+$</td>
<td>±0.0005</td>
</tr>
<tr>
<td>Correction of $\theta_\mu$ and $\theta_e$ for ending in $B_{</td>
<td></td>
</tr>
<tr>
<td>Smearing of $\theta_\mu$ and $\theta_e$ due to measurement error and scattering</td>
<td>±0.0006</td>
</tr>
<tr>
<td>Possible shift in $\theta_e$ due to random hits and inefficiencies in D1 and D2</td>
<td>±0.0005</td>
</tr>
<tr>
<td>Method of averaging $&lt;\cos \theta&gt;$</td>
<td>±0.0004</td>
</tr>
<tr>
<td>Difference in $x=1$ edge calibration between $B_{\perp}$ and $B_{</td>
<td></td>
</tr>
<tr>
<td>Normalization of $B_{</td>
<td></td>
</tr>
</tbody>
</table>
Figure Captions

FIG. 1. Experimental 90%-confidence limits on the $W_{L,R}$ mass-squared ratio $\alpha$ and mixing angle $\xi$ describing possible right-handed charged currents. Muon-decay contours are derived from decay rate measurements at the spectrum endpoint (bold, this experiment); the polarization parameter $\xi P_\mu$ (dotted, Ref. 5); and the Michel parameter $\rho$ (solid, Ref. 6). Nuclear $\beta$ decay contours are obtained from the Gamow-Teller $\beta$ polarization (dot-dashed, Ref. 7); the comparison of Gamow-Teller and Fermi $\beta$ polarizations (long-dashed, Ref. 8); and the $^{19}$Ne asymmetry $A(0)$ and $ft$ ratio, assuming CVC (short-dashed, Ref. 9). Limits from the $y$ distributions in $\nu N$ and $\bar{\nu}N$ scattering (double lines, Ref. 10) are valid irrespective of the $\nu_R$ mass. One experiment (dotted contour) is marginally inconsistent with $\alpha = \xi = 0$ at the 90% confidence interval; for clarity, the corresponding inner contour is suppressed.

FIG. 2. Plan view of muon polarimeter at TRIUMF. "Surface" $\mu^+$ are incident from the top. After crossing proportional wire chambers P1 and P2 and scintillator S1, the muons stop in a foil target within the uniform region of a 1.1-T spin-holding longitudinal field, or alternately a 70-gauss spin-precessing field. After registration in P3, S2, and driftchambers D1 and D2, the decay positron is focussed by the solenoidal field lens between D2 and D3, and analyzed by the $98^\circ$ horizontally focussing spectrometer consisting of D3, D4, and the cylindrical dipole magnet. The trigger is $T1 \cdot T2$, where $T1$ is $P1 \cdot S1 \cdot P2 \cdot \bar{V}1 \cdot \bar{P}3 \cdot S2 \cdot \bar{V}2$ at the $\mu^+$ stopping time, $T2$ is $P3 \cdot S2 \cdot S3 \cdot \bar{P}1 \cdot S1 \cdot \bar{V}1 \cdot \bar{P}2 \cdot V2$ at the $\mu^+$ decay time, and $V1$ and $V2$ are veto scintillators surrounding $S1$ and $S2$, respectively (not shown).

FIG. 3. Distributions in the ratio of the positron momentum to its maximum value: (a) with the $\mu^+$ spin $\vec{\sigma}$ precessed about an axis transverse to the direction $\vec{p}_e$ of positron emission; (b) with $\vec{\sigma}$ held so that $2 < \vec{\sigma} \cdot \vec{p}_e > = 0.9850$. The horizontal scale is calibrated by the edge position in (a). Distributions are uncorrected for acceptance; errors are statistical. The solid line in (a) is a fit with parameters which are empirical except at the shoulder; the gaussian part of the resolution is $< 0.2\%$ rms. The fit in (b) is to a linear combination of the shape of (a) with that expected from pure ($\nu - A$) and 100% $\mu^+$ polarization opposite to $\vec{p}_e$. 

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FIG. 4. (a) Time distribution of positrons for $B_{\|}$ data, (b) Time distribution of positrons for $B_{\perp}$ data. In both cases the events are binned in 0.079 μsec intervals. The solid lines correspond to the fit described in the text.

FIG. 5. Time distribution of positrons for $B_{\perp}$ data with fitted lifetime divided out. The solid histogram corresponds to the fit described in the text.
FIG. 1

$\alpha = M^2(W_L)/M^2(W_R)$

$\xi = (W_L - W_R)$ mixing angle

$M(W_R)$ (GeV/c$^2$)
FIG. 3

(a) $\mu^+ \text{spin precessed}$

(b) $\mu^+ \text{spin held}$

$x = \frac{p(e^+)}{p(e^+)}_{\text{max}}$
FIG. 4
ALL TARGETS

FIG. 5
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