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SEARCH FOR RIGHT-HANDED CURRENTS IN MUON DECAY*

Bruno Gobbi
Department of Physics and Astronomy, Northwestern University
Evanston Il. 60201, USA

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Abstract

We report preliminary results of an experiment designed to measure the mass of the right-handed intermediate vector boson. The presence of such a particle in electroweak interactions is predicted by left-right symmetric gauge theories. The experiment measures the momentum spectrum of the positrons from the decay at rest of 1) longitudinally polarized muons produced in the decay at rest of $\pi^+ \to \mu^+\nu$ (polarization P_μ) and 2) unpolarized muons. The endpoints of these two spectra are used to determine the quantity ξP_μ where ξ is a Michel parameter. This product is related to the ratio of the mass of left and right handed W and to the phase between the two helicity states. We measure, at the 90% CL, $1 - \xi P_\mu \frac{\delta}{\rho} < 0.0041$ and infer the mass $M(W_R) > 380$ GeV/c^2.

The present standard model of weak and electromagnetic interactions is based on the gauge group

$$SU(2)_L \times U(1).$$

The V-A character of β and μ decay is imposed on the theory by allowing only left handed components of fermions to couple to intermediate vector bosons ($W_L^\pm$). The possibility that both left-handed and right-handed fermions participate in β decay has been suggested [1)2)3)] and models have been proposed for which the weak interaction is left-right symmetric at the lagrangian level. These models are

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*) J. Carr. G. Gidal, A Jodidio, K.A. Shinsky, H.M. Steiner D. Stoker, M. Strovink, and R.D. Tripp, U. of Calif. Berkeley and B. Gobbi, Northwestern U. and C.J. Oram, TRIUMF.

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based on the gauge group

$$SU(2)_L \times SU(2)_R \times U(1)$$

which is completely left-right symmetric, except for the masses of the Higgs scalars. Due to spontaneous symmetry breaking the mass of the right-handed charged meson W_R is much heavier than the W_L and its effects are then manifest slow below the energy scale of the W_R mass. The V-A character of the interaction is the result of a natural suppression of right-handed gauge current. The mass eigenstates W_1 and W_2 are linear combinations of the helicity eigenstates W_L and W_R:

$$W_1 = W_L \cos\zeta - W_R \sin\zeta ,$$

$$W_2 = W_L \sin\zeta + W_R \cos\zeta .$$

It is this mixing and mass splitting that induces the observed parity violation. At an energy scale much larger than the W_R mass all interactions are supposed to be parity conserving.

The experiment described here is an attempt to measure the mass of the right handed gauge boson (W_R). The present experiment searches for the W_R by examining its effects on the decay $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$. With this approach the sensitivity achievable with a very high energy experiment is obtained at low energy with a very precise measurement.

The mixing angle ζ between left and right handed currents and α, the square of the ratio of the W's masses,

$$\zeta \equiv (W_L\text{-}W_R) \text{ mixing angle}$$

$$\alpha \equiv M^2(W_L)/M^2(W_R) \tag{1}$$

are the phenomenological parameters which provide a convenient physical description of right-handed charged-current.[2] These two quantities which parametrize the amount of V+A are related to correlations measured in weak decays. [See M. Strovink[4] for a summary of experiments sensitive to V+A.]

The experiment we describe here is a measurement of the e^+ momentum spectrum from the decay of longitudinally polarized μ^+. Such a spectrum, after summing over positron spins, assuming zero mass neutrinos and neglecting radiative corrections is described by the following expression:

$$\frac{d^2\Gamma}{x^2 dx d\cos\theta} = (3-2x)+(\tfrac{4}{3}\rho-1)(4x-3)+12(\frac{m_e}{m_\mu}x)(1-x)\eta$$
$$-[(2x-1)+(\tfrac{4}{3}\delta-1)(4x-3)]\,\xi P_\mu \cos\theta \; . \tag{2}$$

The variable x is the reduced positron momentum ($x \equiv p(e^+)/p(e^+)_{max}$), θ is the angle between μ^+ spin and the e^+ momentum and P_μ is the polarization of the μ^+

from π^+ decay at rest.

The quantities ρ, δ, η, and ξ are the Michel parameters and they are tabulated below along with the expected values from the V-A theory and their experimental values.[5] The quantity measured in the present experiment is the

Parameter		(V - A) Value	World Average	Ref.
"Symmetric Shape"	ρ	3/4	.7517 ± .0026	6)
"Asymmetric Shape"	δ	0.0	-.12 ± .21	7)
"Low Energy parameter"	η	1.0	.972 ± .014	8)
"Polarization Parameter"	ξP_μ	3/4	.7551 ± .0085	9)

Table I. The Michel parameters.

product $\xi P_\mu \frac{\delta}{\rho}$ which in the limit $x \to 1$ and $\cos\theta \to -1$, is related[10] to α and ζ by the approximate relation:

$$\xi P_\mu \frac{\delta}{\rho} - 4(\alpha^2 + \alpha\zeta + \frac{1}{2}\zeta^2). \qquad (3)$$

Experiments measuring ξ always determine the product ξP_μ. A V+A contribution to the $\pi^+ \to \mu^+\nu_\mu$ decay does effect P_μ by $|P_\mu| = 1-2(\alpha+\zeta)^2$; the sensitivity to α

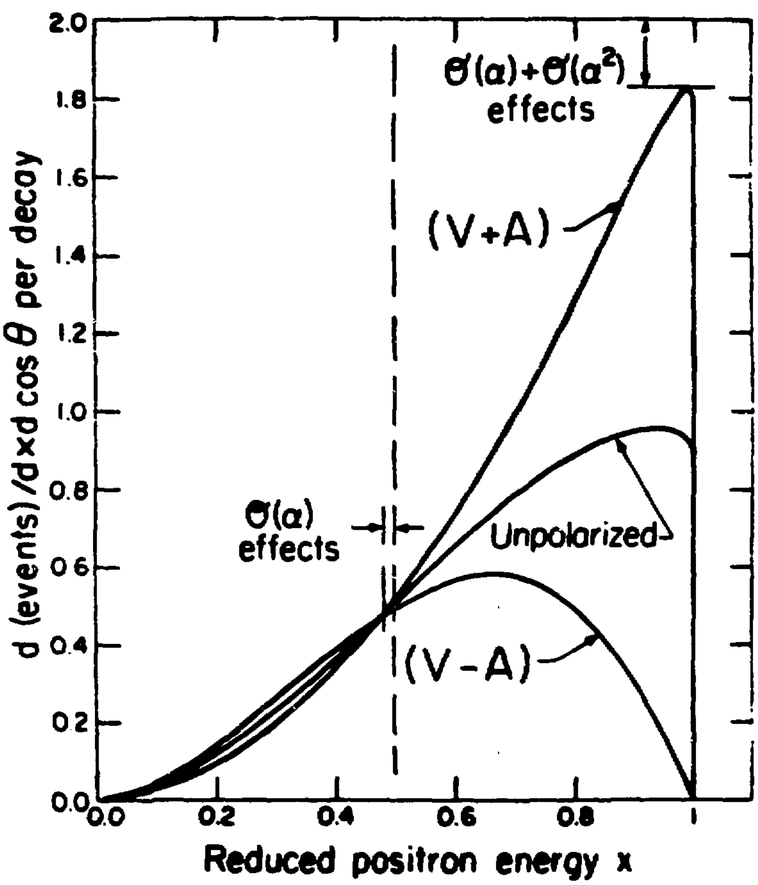

Figure 1: Positron momentum spectrum expected from decay at rest of polarized μ^+ decay via V-A (e^+ detected opposite to muon spin direction) and V+A currents. Also the expected spectrum from unpolarized μ^+ decays.

and ζ, over the entire range of x, is nearly doubled. For x=1 and $|\cos\theta|=1$, the sensitivity to α and ζ is very similar. The Michel parameters δ and η have the same value independently of the helicity of the coupling and ρ, for a V+A interaction is: $\rho=1-2\zeta^2$.

Equation (2) when rewritten with the theoretical values for ρ, δ, and η, and evaluated at $x \to 1$ and $\cos\theta \to -1$ give

$$\frac{d^2\Gamma}{dx d\cos\theta} \to 4(1-x)+(1+\cos\theta)+(1-P_\mu)+ (1-\xi).$$

A measurement of the positron spectrum at the endpoint determines directly the quantity ξ.

Figure 1 shows the expected momentum spectrum of positrons produced from the decay at rest of longitudinally polarized muons when the e^+ are emitted opposite to $\vec{S}_\mu$; both for the case where the decay is mediated by a left-handed current V-A and by a right-handed current V+A. Also shown is the momentum spectrum for the decay of unpolarized muons. These three spectra display two important features of this experiment. First, at x=1 the spectrum associated with a W_L vanishes, while the one associated with a W_R peaks. Second, the spectrum from unpolarized muon decay at x=1 is similar to the one expected from pure V+A contribution. To determine the product $\xi P_\mu \frac{\delta}{\rho}$ we measure two quantities: the spectrum of both unpolarized and polarized muons. The first measurement determines the shape and the second measurement the magnitude of the effect expected.

<u>The Surface Muon Beam</u>

This beam line is described in details by C. Oram[11]. The 100μA, 500 MeV beam of the TRIUMF cyclotron (beamspot $\Delta x \sim$ 2mm, $\Delta y \sim$ 4mm) hits a 2mm thick carbon target. The beam has a 43 ns RF structure. Pions produced inside the target when decaying ($\pi^+ \to \mu^+\nu$) at rest will produce muons with 4.1 KeV kinetic energy and momentum 29.5 Mev/c (β = .271), they have helicity -1 in the case of V-A decays and equal to $|P_\mu| = 1-2(\alpha+\zeta)^2$ for left-right symmetry cases. The beam line makes an angle of 135° with respect to the proton beam. It is 9.6m long, includes two 60° bends and has an acceptance Δx = 35, Δy = 70 mrad. The flux of beam particles is plotted in figure 2 as a function of the beam momentum. The broad distribution of muons at about 25 MeV/c comes from the decay of pions that stop inside the target. Muons with less than 29.5 MeV/c are partially depolarized because they have undergone multiple scattering (coulomb scattering is relativistically helicity conserving and non relativistically spin conserving). The beam line, when used for a polarized beam, is tuned for particles with 29.5 MeV/c and has a $\Delta p/p$ = .5% to ensure the acceptance of only μ^+ coming from the decay of π^+ that stop in a thin layer (6.2 mg/cm^2) at the surface of the target which faces the transport system (hence the name "surface"

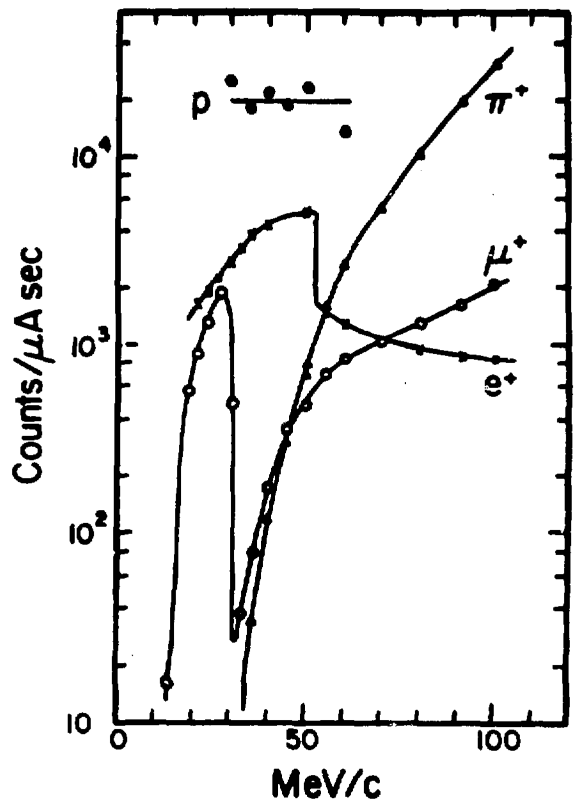

Figure 2: Flux of particles in the M_{13} beam line at TRIUMF[11]) as a function of the beam line momentum. Primary proton beam has 500 MeV, production target is 2 mm thick carbon.

muon beam). Muons from π^+ decay in flight, that are accepted by the beam line are less polarized and are correlated in time with the RF of the cyclotron beam. Such muons (called "cloud" muons) are rejected by looking at their time correlation with respect to the accelerator RF structure. Figure 3 shows the time structure of surface muons.

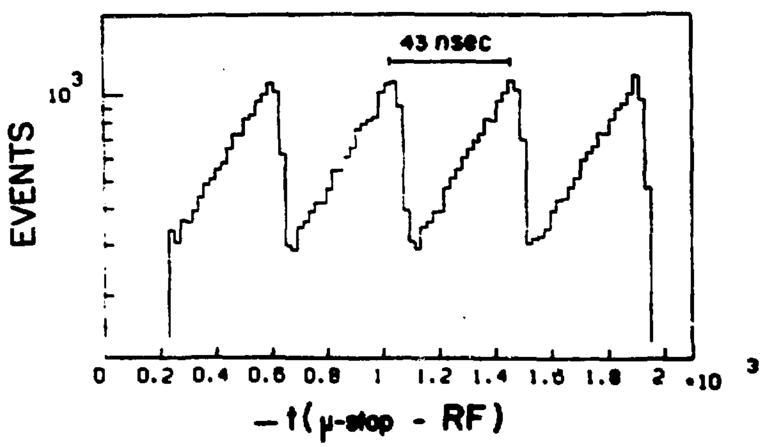

Figure 3: Timing of μ^+ with respect to cyclotron RF (time scale running from right to left) for "surface" muons with beam line at 29.5 MeV/c. The data reproduces the π^+ life time.

The Spectrometer.

The apparatus is sketched in figure 4. It consists of a target where the μ^+ are stopped followed by a cylindrical solenoid to increase the acceptance, and a 98° bend spectrometer where the positrons are momentum analyzed. Two sets of data are collected: the spectrum of e^+ from the decay of polarized and unpolarized muons. For each cases the spectrometer accepts e^+ with reduced momentum in the range $.8 < x < 1.2$. The target in which the μ^+ are stopped is a thin metallic foil (Al, Cu, Ag, or Au). When the spectrum of polarized muons is recorded, a 11k Gauss longitudinal magnetic field is applied to the target region to prevent the muon from depolarizing (Paschen-Bach effect). Unpolarized muons are produced by precessing the μ^+ in a 70 gauss transverse field applied to the area of the stopping target. The magnetic field in the target region is the only parameter of the spectrometer which is changed when the two sets of data (polarized and unpolarized μ^+ decay) are collected.

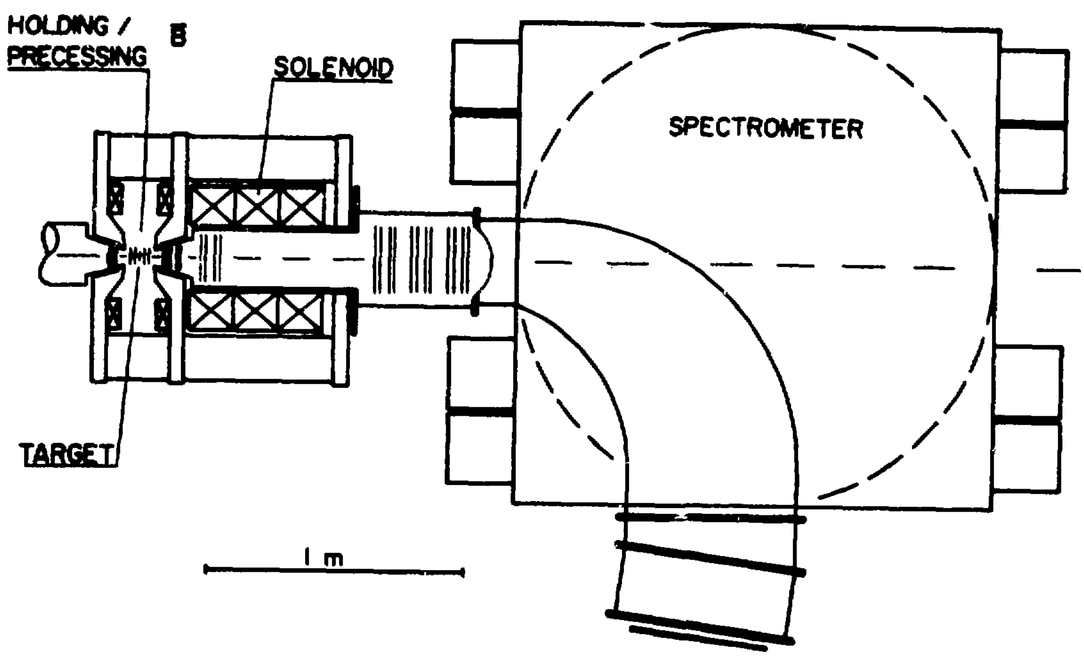

Figure 4: Top view of the spectrometer used to measure ξP_μ.

The direction of the incident μ^+ is measured by two sets of proportional chambers, with x,y read out, and the μ^+ are timed with the signal from a 120 μm thick scintillator counter. The proportional chambers also measure the dE/dx of the beam particles (~60% e^+ and 40% μ^+). The direction of the positron emerging from the target is recorded by an x-y proportional chamber and by two sets of drift chambers placed at the beginning of a solenoid magnet. A scintillation counter (250 μm thick) downstream of the target, times the decay of the μ^+.

The solenoidal magnet has a field of 10 Kgauss and accepts positrons emitted up to 200 mrad from the beam axis; it acts as a field lens which makes the e^+ parallel to the beam at the entering vacuum window of the analyzing magnet. Another set of drift chambers is located at the entrance and in the focal plane of the spectrometer magnet, this last set is followed by scintillation counters. The e^+ trajectory is measured by 24 drift chamber planes in addition to the PWC downstream of the target. The spectrometer has 576 drift chamber wires. All chambers are operated with a mixture of 92% methane and 8% methylal. The distribution of the electron drift distance versus time relation, in the gas of the chambers, is constantly updated as the computer program reconstructs the particles trajectories. With this technique we achieve a spatial resolution of σ = 200 μm and the momentum resolution $\Delta p/p$ = .2% RMS.

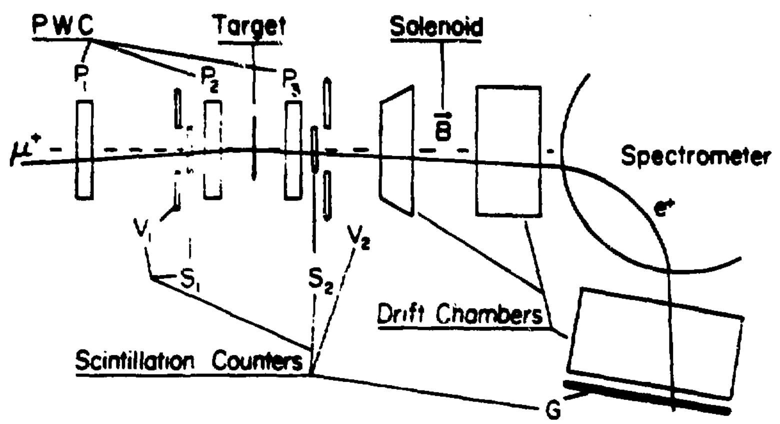

Figure 5: Schematic arrangement of the detector components. The "μ-stop" signal is defined by $P_1.P_2.S_1.\overline{V_1}.\overline{P_3}.\overline{S_2}$ and is generated at a time t_1. The "μ^+-decay" trigger signal is defined by (μ-stop)$.P_3.S_2.G.\overline{V_2}.\overline{P_1}.\overline{S_1}.\overline{V_1}.\overline{P_2}$ and takes place at a time t_2 ($.2 < t_2 < 10$ μsec) after t_1. Beam rates are ~15 KHz and trigger rates ~20 Hz.

The momentum resolution is determined from the shape of the endpoint spectrum for unpolarized muons; it is based on data collected over a period of 3 weeks. Figure 5 shows how the trigger is formed. Data are collected by cycling the four targets. For each, a spectrum with ~100 k events is recorded for both polarized and unpolarized muons. Each spectrum takes about 1 hour to acquire.

Data

The spectrometer was operated twice in 1982, in the spring and in the fall. The data collected in the spring have been analyzed and the results are presented here; they are based on 3.5 x 10^6 stopped muons. In the fall run another 10^7 events were logged. 99% of the recorded events have a μ^+ track entering the target, followed after 200 ns or later by an e^+ going

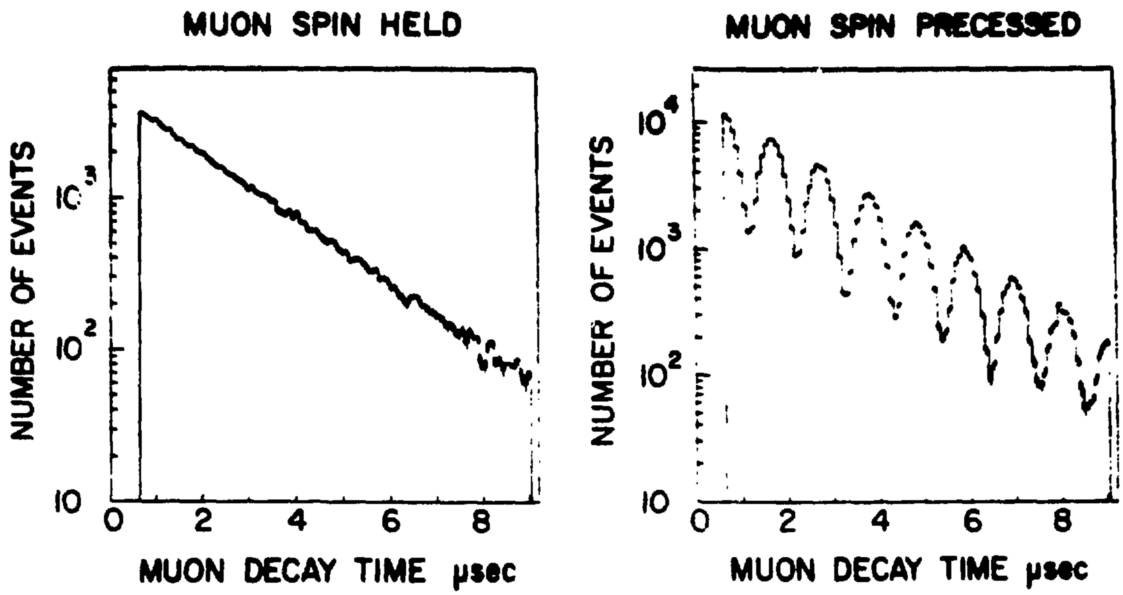

Figure 6: Muon decay time for polarized muon beam (left). Decay time when muons are precessed in a 70 Gauss transverse field (right).

through the spectrometer. Only events satisfying the following track reconstruction criteria are retained: no hits in the chambers in addition to the one used to reconstruct track segments, track segments must join in a continuous sequence, and the particle trajectory must be well within the sensitive volume of the spectrometer.

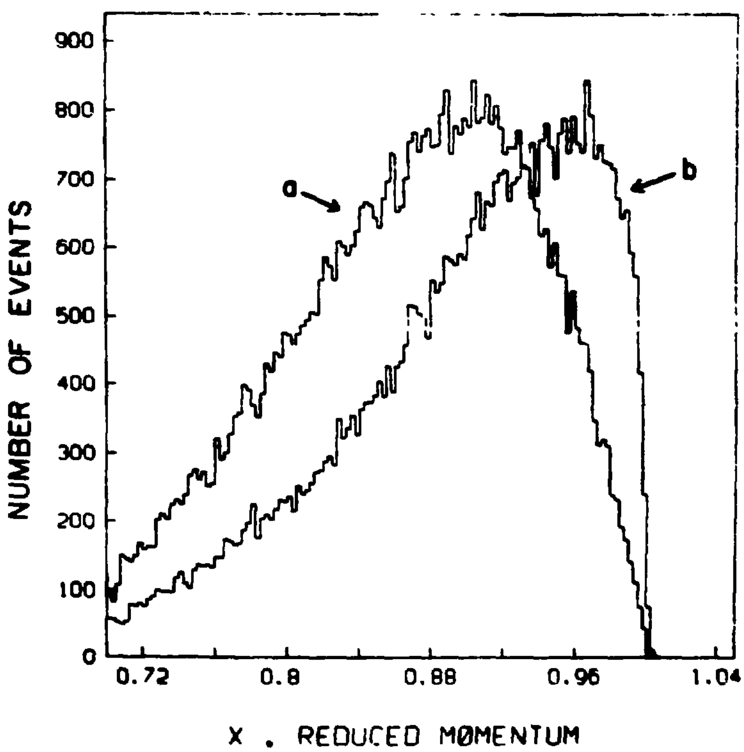

Figure 7: Reduced momentum spectrum for positrons from decay at rest a) of longitudinally polarized μ^+ and b) of unpolarized muons.

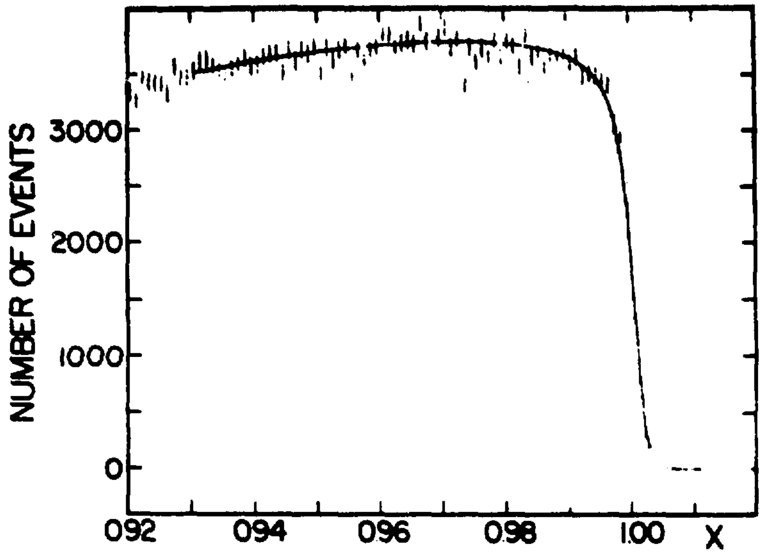

Figure 8: Reduced momentum spectrum for unpolarized muons. The curve is the prediction of the V-A theory. The shape of this curve at its endpoint is the same as expected in the case of a pure V+A interaction. In the text this function is called $f_+(x)$. This plot includes 175K events, collected with four stopping targets.

The time distribution of the μ^+ decay for both polarized and unpolarized muons are shown in figure 6. Both plots confirm that we are observing background free μ^+ decays. The momentum spectra for the e^+ are shown in figure 7. The quantity $\xi P_\mu \frac{\delta}{\rho}$ is obtained by considering these two spectra in the region x > .92 and cosθ > .975, obtained with only "surface" μ^+ (timing not correlated with RF).

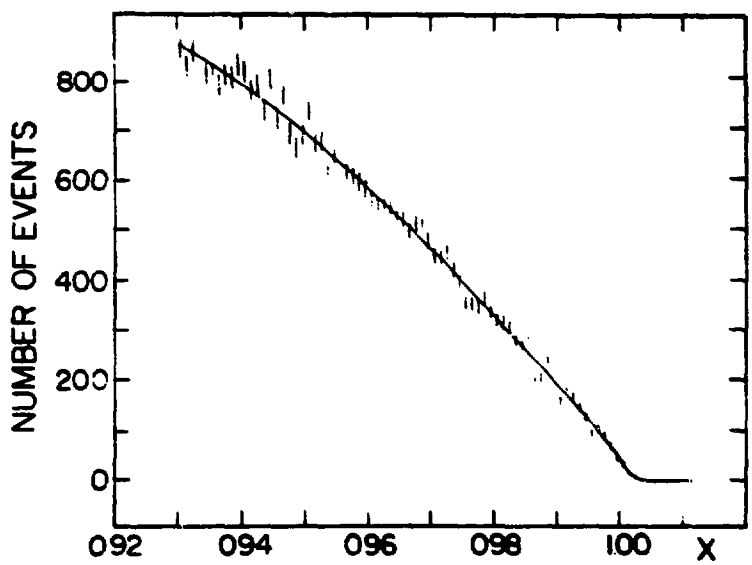

Figure 9: Reduced momentum spectrum of positrons from the decay at rest of longitudinally polarized μ^+. See text for an explanation of the curve fitted through the data. There are 89k events in the plot.

The analyzed spectrum, from unpolarized μ^+ decays, is shown in fig. 8. The curve is a fit to the data with the spectrum shape predicted by the V-A theory including radiative corrections [12] and Bhabha's production in material. From the fit we can determine the spectrometer acceptance and its resolution at x=1, and the shape of the momentum distribution as expected by the V+A interaction. We denote this function as $f_+(x)$. The fit to this set of data is now used to calculate the shape of the endpoint positron spectrum as expected from a pure V+A interaction for the decay of polarized muons. We denote this function as $f_-(x)$. The spectrum of e^+ from polarized muons (fig. 9) is divided by the one for unpolarized μ^+ in order to eliminate to first order the spectrometer acceptance. This ratio is then fitted, for different intervals of cos θ, to the sum of the V-A contribution to the interaction ($f_-(x)$) plus some contribution due to the V+A interaction which shape is given by $f_+(x)$:

$$\text{ratio (polarized/unpol.)} = f_-(x) + \xi P_\mu \cos\theta \frac{\delta}{\rho} f_+(x) .$$

The quantity $\xi P_\mu \frac{\delta}{\rho}$ obtained from fitting the data at different intervals of cos θ is plotted in figure 10. The limit of the variable at $|\cos\theta| = 1$ gives us the quantity we desire. The result obtained from the data for each of the four targets is plotted in figure 11. The four values are consistent. Before using our value for $\xi P_\mu \frac{\delta}{\rho}$ in equation 3 to determine the mass of the W_R the measured quantity must be corrected for μ^+ depolarization due to multiple

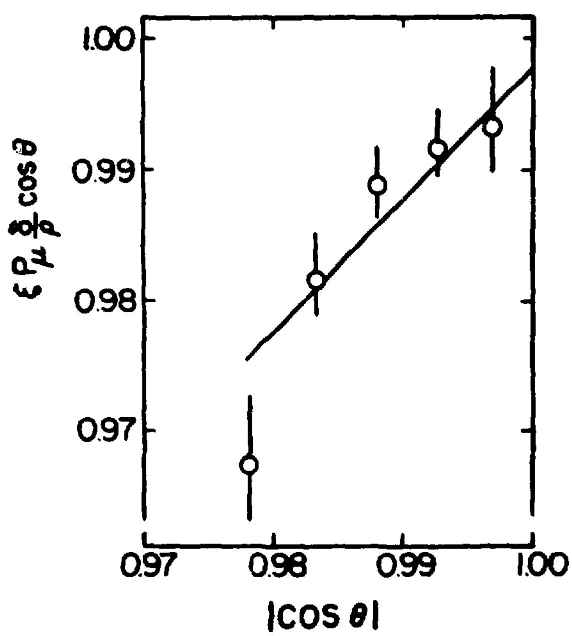

Figure 10: The quantity $\xi P_\mu \cos\theta \frac{\delta}{\rho}$ is plotted as function of cos θ. The slope of the linear fit to the data is taken from the theory. The intercept of this line at $|\cos\theta| = 1$ determines the quantity $\xi P_\mu \frac{\delta}{\rho}$ at $x \to 1$ and $|\cos\theta| \to 1$.

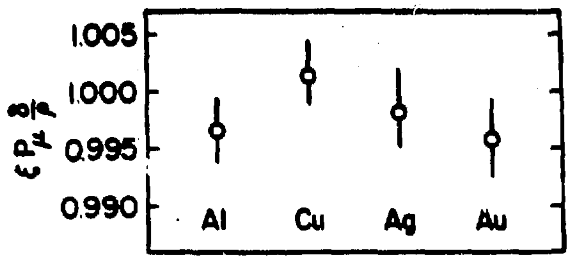

Figure 11: The quantity $\xi P_\mu \delta/\rho$ determined from data taken with different stopping targets is shown. The four results are in agreement showing that if muons depolarize in the target, depolarization takes place at an equal and extremely small level in all four targets.

scattering. The amount of material in the production target and upstream of the stopping target is 24.6 mg/cm^2 with a radiation length of .654 x 10^{-3} X_0; the calculated correction factor is 1.0012 ± .005. Possible depolarization of the beam in the stopping target foil has not been included, but can only strengthen the limit that we present.

Results

The preliminary results from the first set of data are presented as a 90% C.L. limit

$$1 - \xi P_\mu \frac{\delta}{\rho} < 0.0041 \text{ (90\% CL)} .$$

When used in conjunction with Eq. 3 the following limits (90% CL) were obtained for $M(W_R)$ assuming $M(W_L)$ - 80 GeV/c^2, and zero mass neutrinos

$$\zeta \text{ free} : \alpha < 0.045 \qquad M_R > 380 \text{ GeV/c}^2$$

$$\zeta \text{ fixed to } 0 : \alpha < 0.032 \qquad M_R > 450 \text{ GeV/c}^2 .$$

The limits on the phase ζ between left-and right-handed currents are:

$$\alpha \text{ free} : -0.064 < \zeta < 0.045$$

$$\alpha \text{ fixed to } 0 : -0.045 < \zeta < 0.045 .$$

These results are displayed graphically in figure 12 together with the currents limits on right handed currents[17)]. Theoretical predictions varies between 1.6 TeV/c^2 [13)] and as low as 220 GeV/c^2 [14)].

I would like to extend my appreciation to the organizers of the XIIIth Rencontre de Moriond for giving me the opportunity to spend an exciting week at this interesting meeting. Many thanks to my colleagues on this experiment for their help in preparing this material and to R. Oakes for many helpful discussions on the subject.

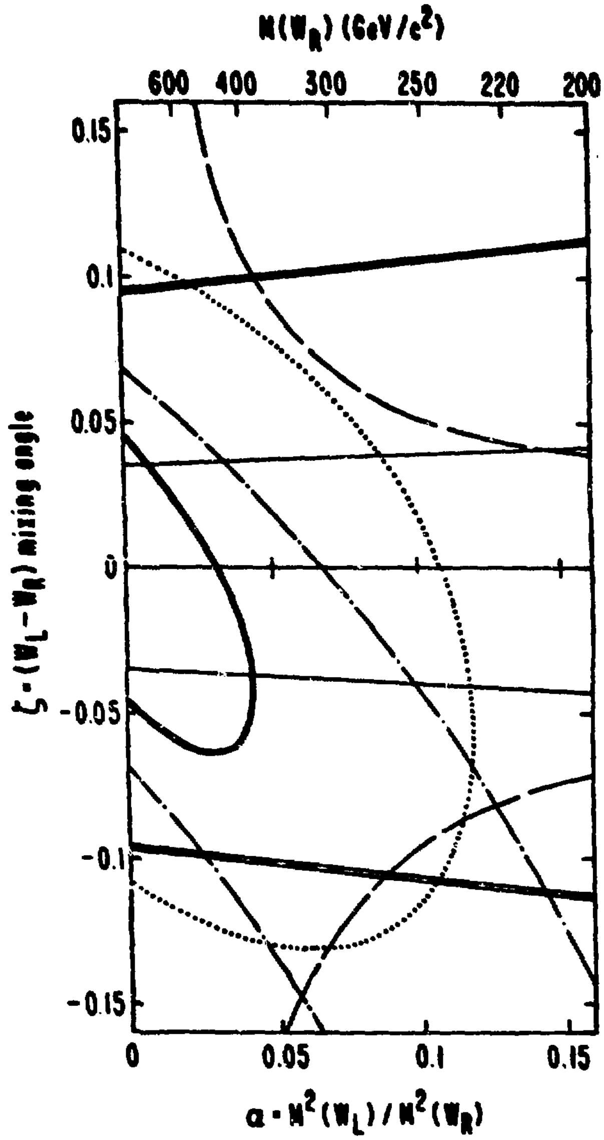

Figure 12: Plots of existing 90% CL limits on the phenomenological quantities α and ζ describing right-handed currents. Contours are derived from measurements of the polarization parameter ξP_μ (bold, this experiment, dotted, Ref. 9); the polarization of the β decay in Gamow-Teller transitions (dot-dashed, Ref. 15). Limits from the y distributions in νN and $\bar{\nu} N$ scattering (double line, Ref. 16) are valid irrespective of the ν_R mass.

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