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ABSTRACT

The status of the quark mixing matrix is reviewed. New lower bounds on \(|\sin \delta|\) and on \(\beta/\sin \theta\) in the Maiani representation follow from a maximum top quark mass of 50 GeV. Recent data relevant to possible \(S, P, T\) couplings are reviewed, and new results on muon decay parameters \(\eta\) and \(\delta\) are presented. A new measurement of \(\xi P_\mu \delta/\rho\) by a different technique has confirmed the recently published stringent new limit. Constraints on a possible right-handed \(W\) and the effect of various assumptions concerning the associated right-handed neutrino are discussed.

1. Introduction

In this short review I first shall discuss the flavor structure of hadronic charged currents (i.e. the Kobayashi-Maskawa matrix) and then their spacetime structure. The latter topic will begin with a mention of experimental input relevant to possible \(S, P, T\) interactions, followed by discussion of the constraints on a possible right-handed \(W\).

Flavor structure of leptonic currents at this conference is the responsibility of Lincoln Wolfenstein; neutral weak currents are discussed in a separate session by a number of speakers. Structure functions in charged-current interactions are reviewed by Arie Bodek. My talk will draw upon \(b\) lifetime and branching ratio data reviewed by Klaus Schubert, and will refer to \(CP\)-noninvariance parameters discussed here by Bruce Winstein.

2. Quark Mixing Matrix

In general the \(Q=\frac{3}{2}\) quarks couple to a set of \(Q=-\frac{3}{2}\) states that are related to the \(Q=-\frac{1}{2}\) flavor eigenstates by a unitary transformation. With three generations, the 9 parameters of a general \(3\times3\) unitary matrix can be reduced to 4, since the relative phases of six quarks are otherwise arbitrary. These parameters take the form of three angles needed to describe a general Euler rotation, and one phase that is zero if \(CP\) is conserved:

\[
U = R_{sb}(\theta_{2}) \ U_{CP}(\delta) \ R_{ds}(\theta_{1}) \ R_{sb}(\theta_{3})
\]  

(2.1)
FIG. 1. The quark mixing matrix in the Kobayashi-Maskawa and Maiani forms. $c_i$ and $s_i$ denote the cosine or sine of $i$. 
with $R_{ij}$, an ordinary rotation matrix in the $ij$ plane, and $U_{ij}$ a diagonal matrix with elements 1, 1, and $e^{i\delta}$. The product, in a form slightly different from that first written down by Kobayashi and Maskawa, is shown in Fig. 1. Here $\theta_1$ is nearly the Cabibbo angle, and $\theta_2$ and $\theta_3$ are the mixing angles that couple $b$ quarks to $c$ and $u$ quarks, respectively. Also shown is an alternate parameterization due to Maiani, which shifts some of the algebraic complexity to elements that are not yet measured. The parameters are again nearly the Cabibbo angle; mixing angles $\gamma$ and $\beta$; and the CP-violating phase $\delta'$. Although not rigorous, it is nevertheless helpful to associate $\gamma$ with $\theta_2$, and $\sin\beta/\sin\theta$ with $\sin\theta_3$. Other parameterizations have been proposed, for example by Wolfenstein and by Chau and Keung. The choice of mixing matrix parametrization affects the ease of phenomenological analysis, but cannot alter any physical prediction. The matrix elements are among the basic parameters of the standard model.

2.1. Cabibbo angle

Recently the WA2 collaboration at the CERN SPS have measured the hyperon decay channels

$$\Sigma^- \rightarrow n e^- \bar{\nu}$$
$$\Sigma^- \rightarrow \Lambda e^- \bar{\nu}$$
$$\Xi^- \rightarrow \Lambda e^- \bar{\nu}$$
$$\Sigma^{0} \rightarrow \Xi^- e^- \bar{\nu}$$
$$\Lambda \rightarrow p e^- \bar{\nu}$$

Their Cabibbo fit also included the neutron lifetime. They obtained

$$U_{us} = \sin\theta_1 \cos\theta_3 = 0.231 \pm 0.003 \ . \quad (2.2)$$

We shall see that $\cos\theta_3$ is negligibly different from unity. In a recent preprint, Leutwyler and Roos considered the above data — allowing for SU(3) symmetry breaking in $g_A$ — and also included data from the reactions

$$K^+ \rightarrow \pi^+ e^+ \bar{\nu}$$
$$K^0 \rightarrow \pi^0 e^+ \bar{\nu}$$

together with theoretical values for $f_+ K^0 \pi^-$ and $f_+ K^+ \pi^0$. They obtained

$$U_{us} = 0.221 \pm 0.002 \ . \quad (2.3)$$

Evidently (2.2) and (2.3) cannot both be right.

2.2 b mixing angles

2.2.1 b lifetime measurements

A revolution in quark mixing matrix phenomenology has followed the introduction of vertex detectors at PEP and the measurement there of lower as well
as upper limits to the $b$ lifetime. The PEP results are:

- (Mark II) $\tau_b = 1.20 \pm 0.45 \pm 0.3 \text{ psec}^{7}$
- (MAC) $\tau_b = 1.6 \pm 0.4 \pm 0.3 \text{ psec}^{8}$

The earlier JADE upper limit$^{9}$ is 1.4 psec (95% confidence). The easiest average to compute is that of the two experiments (2.4) and (2.5), which quote definite central values:

$\tau_b = 1.4 \pm 0.4 \pm 0.3 \text{ psec}$

or

$0.8 < \tau_b < 2.0 \text{ psec} \ (90\% \text{ confidence}) \ (2.6)$

Here I have assumed that the two PEP experiments are not systematically independent. I shall use the range (2.6) of $b$ lifetimes in the following discussion. More complete averages, incorporating the JADE limit and/or including unofficial new results from PEP, will tend to bring the central $b$ lifetime closer to 1 psec, while still definitely excluding a lifetime near 0.0 psec. Allowed mixing angle ranges vary only as the square root of this parameter.

2.2.2 $B$ branching ratios

The relative branching ratio for $B$ mesons decaying semileptonically to $c$ or $u$ quarks is measured by analyzing the daughter lepton energy spectrum. The CESR results are:

- (CLEO) $\Gamma(B\to u)/\Gamma(B\to c) < 0.04 \ (90\% \text{ confidence}) ^{10}$
- (CUSB) $\Gamma(B\to u)/\Gamma(B\to c) < 0.055 \ (90\% \text{ confidence}) ^{11}$

At this conference K. Schubert$^{12}$ has also reported related new data from ARGUS at DORIS. Despite his penetrating comments on the subtleties of these analyses, I shall accept at face value the interpretation of the CESR data presented at Erice by J. Lee-Franzini,$^{13}$ and use her result

$|U_{ub}/U_{cb}| < 0.12 \ (90\% \text{ confidence}) \ (2.9)$

2.2.3 Kobayashi-Maskawa angles

If $\delta$ is allowed to vary over $2\pi$, both $\sin \theta_2$ and $\sin \theta_3$ can be constrained to be positive. The allowed region is represented by a set of contours parameterized by $\delta$, as shown in Fig. 2. From Ref. 13,

$\tau_b^{-1} \ (\text{psec}^{-1}) = 368|U_{cb}|^2 + 780|U_{ub}|^2 \ (2.10)$

The equations governing the contours are easily obtained by inspection of Fig. 1. In the numerical work I have used (2.6), (2.9), and a value of $\sin \theta_1$ halfway between (2.2) and (2.3).
FIG. 2. Bounds on the Kobayashi-Maskawa b mixing angles $\theta_2$ and $\theta_3$, with the CP-violating phase $\delta$ as a parameter. The allowed regions include $\sin \theta_2 = 0.05$, $\sin \theta_3 = 0$. 
2.2.4 Maiani angles

With the same numerical input, \( \sin \gamma \) and \( \sin \beta / \sin \theta \) are restricted by a single contour independent of the \( CP \)-violating phase \( \delta' \), as shown in Fig. 3. For this reason the rest of my discussion will be based on the Maiani parametrization (though it could at least as conveniently use that of Wolfenstein or of Chau and Keung). Note again that the upper limit on \( \sin \gamma \) corresponds to the lower limit on the \( b \) lifetime. Without the latter I would be plotting \( \sin \gamma \) and \( \sin \beta / \sin \theta \) from 0 to 1, displaying 100 times the area.

2.3 Restrictions from \( CP \) noninvariance and the top quark mass

As calculated e.g. by Paschos, Stech and Türke, the magnitude of the \( K_L^0 - K_S^0 \) mixing parameter \( \epsilon \) is given to good approximation by

\[
|\epsilon| = \frac{B \sin \beta \sin \gamma \sin \delta'}{\sin \theta} \left( 1 + \frac{n_2}{n_1} \frac{m_t^2}{m_c^2} + \frac{n_2}{n_1} \frac{m_t^2}{m_c^2} \left[ \sin^2 \gamma - \frac{\sin \beta \sin \gamma \cos \delta'}{\sin \theta} \right] \right)
\]

(2.11)

where \( m_c \) and \( m_t \) are charm and top quark masses, \( n_1, n_2, \) and \( n_3 \) are QCD corrections, and

\[
B = \frac{\langle K^0|\bar{s}d\rangle_L (\bar{s}d) L \mid K^0 \rangle}{\langle K^0|\bar{s}d\rangle_L \mid 0 \rangle \langle 0|\bar{s}d\rangle_L \mid K^0 \rangle}
\]

(2.12)

is the \( K^0 - \bar{K}^0 \) transition matrix element normalized to its "vacuum insertion" value. The PCAC value of \( B \) is 0.33, but various authors have speculated that it could be as large as unity. Guberina, Machet, and de Rafael have derived a firm upper bound on \( B \); following Kleinknecht I shall take a conservative value \( B = 2.6 \) that is representative of their bound. The following numerical work makes use of QCD corrections calculated by Gilman and Wise with \( \Lambda = 100 \) MeV/c (slightly stronger restrictions on Maiani angles would arise from using larger values of \( \Lambda \)).

At this conference Carlo Rubbia presented first evidence for production and semileptonic decay of top quark states in the UA1 experiment at the CERN \( pp \) collider, with a range of possible top quark masses

\[
30 \leq m_t \leq 50 \text{ GeV}.
\]

(2.13)

Combining (2.11) and (2.13) with the known \( CP \)-noninvariance magnitude

\[
|\epsilon| = (2.28 \pm 0.05) \times 10^{-3}
\]

(2.14)

produces a set of contours depending on \( \delta' \) as well as on the exact value of \( m_t \).

These contours may be used in at least two ways. If \( \delta' \) is fixed to 170°, a band of contours is produced (Fig. 4) that barely intersect the region allowed by \( b \) lifetime and \( B \) branching ratio measurements discussed earlier. (If \( \delta' \) is fixed to 100°, the disagreement is worse.) Considering the very conservative value of \( B \) upon which these contours are based, it seems safe to conclude that
FIG. 3. Bounds on the Maiani $b$ mixing angles $\gamma$ and $\beta$, independent of the CP-violating phase $\delta'$. Each of the three segments of the contour is the 90%-confidence bound due to the datum indicated.
FIG. 4. Contours set by fixed values of the CP parameter $|\epsilon|$, $\delta'$, and the normalized $K^0-\bar{K}^0$ transition matrix element $B$ as indicated (see text), with the top quark mass as a parameter, superimposed on Fig. 3. The nearly vanishing overlap and the conservative value of $B$ indicate that $|\sin \delta'| \geq \sin 10^\circ$ if $m_t \lesssim 50$ GeV.
FIG. 5. Contours set by fixed values of $|\epsilon|$ and $B$, and with $\delta'$ set to $90^\circ$, giving a near maximum calculated value of $|\epsilon|$. The top quark mass is a parameter. Within the region of overlap with Fig. 3, $\sin \beta/\sin \theta \geq 0.005$. 

$|\epsilon| = 2.28 \times 10^{-3}$

$\delta' = 90^\circ$

$B = 2.6$

$\sin \beta/\sin \theta$
\[ |\sin \delta'| \geq \sin 10^\circ \quad (2.15) \]

Alternatively (Fig. 5) we may fix \( \delta' \) to 90\(^\circ\), giving close to the maximum \( |\epsilon| \). In this case the contours within the allowed area lie mostly in the region

\[ \sin \beta / \sin \theta \geq 0.005 \quad (2.16) \]

Again in view of the conservative choice of \( B \), this limit seems safe. I emphasize that (2.15) and (2.16) depend completely upon our knowledge of the top quark mass.

2.4 Restrictions from \( |\epsilon'/\epsilon| \)

Positive evidence of CP noninvariance outside the \( K^0 - \bar{K}^0 \) mass matrix would place lower limits on \( |\sin \delta'| \) that are largely independent of the top quark mass. We are perhaps only one experimental generation in advance of such evidence. Further discussion of this point (and of \( B^0 - \bar{B}^0 \) mixing) is deferred to B. Weinsteins review at this conference.

2.5 Mixing of more than three generations

With \( N \geq 3 \) generations the 3x3 submatrix considered here is no longer unitary. Unitarity of the full \( N \times N \) matrix requires the sum of moduli-squared of the elements of each row or column in the 3x3 submatrix to be \( \leq 1 \). Thus the 3x3 submatrix has 13 free parameters with 6 constraints. Therefore, in this more general case, even with the stringent limits imposed by the \( b \) lifetime it is essential to measure as many individual matrix elements as possible.

Charged-current neutrino data with one \( (\nu_e) \) or two opposite-signed \( (\nu_{\mu}) \) muons in the final state can determine \( |U_{cd}| \). For example, using an average semileptonic charm branching ratio of 7.1 \( \pm 1.3\% \), and the relation

\[ \frac{3}{2} B(\text{charm} \rightarrow \mu X) |U_{cd}|^2 = \frac{(\sigma_{\nu \mu} - \sigma_{\nu \mu'})}{(\sigma_{\nu \mu} - \sigma_{\nu \mu'})} \quad (2.17) \]

the CDHS group obtained\(^{18}\)

\[ |U_{cd}| = \sin \theta_1 \cos \theta_2 = 0.24 \pm 0.03 \quad (2.18) \]

To measure \( |U_{cs}| \) from neutrino dimuon data it is necessary to isolate the contribution from the strange sea. This is done by fitting the \( x \) distribution both of neutrino- and antineutrino-produced dimuons. For example, this technique applied to the CDHS data produced the result\(^{18}\)

\[ |U_{cs}/U_{cd}|^2 \geq (9.3 \pm 1.6) \quad (2.19) \]

where the inequality becomes an equality if\(^{19}\)
FIG. 6. Results of Kleinknecht's \(^{16}\) combined fit. At the top are 1σ ranges of moduli of matrix elements (the small numbers indicate the different ranges obtained when there are more than 6 quarks). 1σ ranges of mixing angles in the Kobayashi-Maskawa and Maiani forms are indicated below. Bounds depending on \(m_t\) at the bottom come from Figs. 4 and 5. Values of \(\theta_1\) and \(\theta\) in small type are from Leutwyler and Roos.\(^6\)
\[
\frac{\int x dx [s(x)]}{\frac{1}{2} \int x dx [\bar{u}(x) + d(x)]} = 1.
\]

If three generations are assumed, the analysis can be turned around. With this assumption Kleinknecht\textsuperscript{16} using CDHS data obtains 0.49 ± 0.07 for the left-hand side of (2.20).

2.6 Summary of quark mixing matrix

Kleinknecht\textsuperscript{16} has performed a combined fit to essentially the same data that I have used in the previous discussion. The resulting contours are similar to those in Figs. 2-5, but are rounded by the combined statistical effects. His numerical results are represented in Fig. 6. Within the matrix there, one-standard-deviation ranges for the moduli of the matrix elements are displayed both for the 3-generation case (large type), and for the >3-generation case (differences indicated in smaller type). One-standard-deviation ranges of angle are shown for two parameterizations below. I have made only two additions. At the bottom I have added the restrictions (2.15) and (2.16) that would follow from the new evidence that the top quark mass lies below 50 GeV. And beside the WA2 result (2.2) for the parameters \( \theta_1 \) and \( \theta \) I have added in smaller type the alternate value (2.3) obtained by including \( K_{e3} \) data and allowing for SU(3) symmetry breaking.

Future major advances in quark mixing-matrix phenomenology will follow from direct observation of \( b \rightarrow u \) transitions and of CP noninvariance outside the \( K^0 - \bar{K}^0 \) mass matrix. It will also be important to know the top quark mass better.

3. Spacetime Structure of Charged Currents

3.1 Data constraining possible S, P, and T interactions

I shall first remind you of two recently published experimental results that severely limit models with other than V or A currents. Then I shall discuss related data newly available at this conference.

3.1.1 \( \pi^+ \rightarrow e\nu \) branching ratio

The ratio \( \Gamma(\pi^+ \rightarrow e\nu)/\Gamma(\pi^+ \rightarrow \mu\nu) \) is of order \( (m_e/m_\mu)^2 \) for any combination of V and A current, following the usual helicity-suppression argument. Thus the ratio is enormously sensitive to a possible pseudoscalar exchange which (unlike minimal Higgs exchange) does not couple proportionally to fermion masses. A recently published measurement\textsuperscript{20} performed at TRIUMF is now being repeated with the hope of still greater sensitivity. The method is classic: a low-energy \( \pi^+ \) beam is brought to rest within a stack of thin scintillators, so that no decay \( \mu^+ \) can escape. The decay positron energy is measured in a large NaI crystal, at gated times (i) comparable to the \( \pi^+ \) lifetime, and (ii) much longer than the \( \pi^+ \) lifetime, where no \( \pi^+ \rightarrow e\nu \) signal is expected. Copious lower-energy positrons
from $\mu^+$ decay dominate both samples. Combined analysis of sets (i) and (ii) yields a branching ratio that to first order is independent of the absolute time gate width, the time at which the first gate begins, the $\mu^+$ fraction in the $\pi^+$ beam, and the $\Delta \Omega$ of the $e^+$ detector. The published result is

$$\frac{\Gamma(\pi^+\rightarrow e\nu)}{\Gamma(\pi^+\rightarrow \mu\nu)} = (1.218 \pm 0.014) \times 10^{-4},$$

consistent with the calculated value\textsuperscript{21} $1.233 \times 10^{-4}$.

3.1.2 Polarization of $e^+$ in $\mu^+$ decay

The ETH/Zurich-SIN-Mainz group have been studying both the longitudinal and transverse polarization of $e^+$ from $\mu^+$ decay with a precision that has been improving steadily since the late 1970's. In their spectrometer, polarized muons are stopped and their spins are precessed in a horizontal plane. Decay $e^+$ trajectories both before and after a magnetized foil are measured with proportional chambers; energies of $e^-$ and $\gamma$ as well as $e^+$ are determined downstream of the foil in four NaI blocks. The positron polarization is analyzed both by Bhabha and bremsstrahlung processes in the foil. The results are expressed in terms of the quantities $\alpha/A$, $\beta/A$, $\alpha'/A$, and $\beta'/A$, where $A=16$ and $\alpha$, $\beta$, $\alpha'$, and $\beta'$ are functions of $C'_{vS}$, $C'_{vP}$, $C'_{vV}$, and $C'_{A}$ (see, for example, Scheck\textsuperscript{22}); and in turn the $C'_{ri}$ are the coefficients of $[\bar{e} \Gamma_{i}\mu][\nu \Gamma^{i}(\gamma_{5})_{\nu}e]$ in the charge-retention Hamiltonian. $\alpha'$ and $\beta'$ are $T$ violating and measure $e^+$ polarization out of the (rotating) plane formed by the $\mu^+$ spin and the positron momentum.

The latest available ETH-SIN-Mainz results can be found in their 1983 publication\textsuperscript{23} and in a 1984 Ph.D. thesis:\textsuperscript{24}

\begin{align*}
\alpha/A &= 0.014 \pm 0.107 & (0.016 \pm 0.052) \\
\beta/A &= -0.038 \pm 0.037 & (0.001 \pm 0.018) \\
\alpha'/A &= -0.115 \pm 0.014 & (-0.044 \pm 0.052) \\
\beta'/A &= 0.029 \pm 0.037 & (0.017 \pm 0.018)
\end{align*}

If $C'_{S,P,T}$ are assumed all to be zero, possible deviation of $C_{V}$ and $C_{A}$ from their standard-model values may be parameterized by the small quantity $\epsilon$:

\begin{align*}
C'_{V}/C_{V} &= -\lambda \\
C'_{A}/C_{V} &= \lambda(1+\epsilon) \tag{3.3} \\
C'_{A}/C_{V} &= -(1+\epsilon)
\end{align*}

The authors interpret their results for $\alpha$, etc., in terms of a bound on (complex) $\epsilon$. On cursory examination this notation leaves the impression that a bound on $\epsilon$ is a bound on a possible mixture of $(V+A)$ with the dominant $(V-A)$ current. Unfortunately this is not the case. The coefficients $C_{i}$ parameterize neutral, lepton-flavor-changing currents. Upon Fierz transformation to coefficients $G_{i}$ parameterizing the charged, lepton-flavor-conserving currents corresponding to $W$
exchange, all sensitivity to a possible (V+A) admixture is lost.

The ETH-SIN-Mainz experiment nevertheless is quite sensitive to possible non V,A interactions contributing to $\mu^*$ decay. When their positron polarization data are combined with the Berkeley-Northwestern-TRIUMF result for $\xi P_{\mu} \delta/\rho$ (see below), the $\eta$ parameter in $\mu^*$ decay is found to be consistent with zero within an error of approximately ±0.035. ETH-SIN-Mainz have also measured the longitudinal positron polarization in muon decay to a precision of about ±0.045.

3.1.3 $\eta$ parameter in $\mu^*$ decay

Averaged over positron polarization and to lowest nonvanishing order in $m_e/m_\mu$, the spectrum of reduced positron energy $x$ and angle $\pi-\theta$ relative to the spin direction of a decaying $\mu^*$ is given by

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

where $\rho$, $\eta$, $\delta$, and $\xi$ are the usual muon decay parameters$^{22}$ and $P_{\mu}$ is the polarization of the $\mu^*$ (produced by $\pi^+$ decay at rest in many experiments). The parameter $\eta$ thus is suppressed in its effect on the spectrum except at low energies.

The Berkeley-SIN-TRIUMF group$^{25}$ (Crowe et al.) working at TRIUMF have constructed an annular focussing spectrometer optimized for the low-energy end of the positron spectrum. Positron energies are also measured in a NaI crystal downstream of the focus. The path between the stopping muon target scintillator and the focus is evacuated. A preliminary spectrum based on one-sixth of their data, newly available at the time of this conference, is shown in Fig. 7. The solid line is the (radiatively corrected) standard-model expectation $\eta = 0$. A fit to these data yields their preliminary result

$$\eta = -0.087 \pm 0.097.$$  

(3.5)

3.1.4 $\delta$ parameter in $\mu^*$ decay

As a byproduct of their searches for the effects of a possible right-handed $W$ in muon decay, the Berkeley-Northwestern-TRIUMF group$^{26}$ have measured the angular asymmetry parameter $\delta$. The result, new for this conference, is very preliminary since the data were collected only in January of this year. The method is the same as that of the muon-spin-rotation ($\mu$SR) method used to search for right-handed currents, described in more detail below, except that the range of reduced positron momentum $x$ was extended from 1 to below 0.4. Based on on-line and off-line analysis of a total of 4 of the data, the measured $\mu$SR asymmetry vs $x$ is displayed in Fig. 8. The solid line is the (radiatively corrected) standard-model expectation $\delta = \frac{1}{4}$, also expected in most left-right-symmetric gauge models.

A very preliminary fit, leaving $\xi P_{\mu}$ free but (with negligible effect on the error) fixing $\rho = \frac{3}{4}$, yields
FIG. 7. Positron momentum spectrum from $\mu^+$ decay at rest, used by the Berkeley-SIN-TRIUMF group$^{25}$ in their preliminary determination of the decay parameter $\eta$. 
FIG. 8.Muon spin rotation asymmetry measured by the Berkeley-Northwestern-TRIUMF group in their preliminary determination of the muon decay parameter $\delta$. Where not visible the error bars are smaller than the dots.
\[ \delta = 0.748 \pm 0.004 \text{ (statistical)} \pm 0.003 \text{ (systematic)}, \quad (3.6) \]

where the systematic error arises chiefly from uncertainty in the external (±0.0015) and internal (±0.001) radiative corrections, and in the positron momentum calibration (±0.0015). This is almost a factor of two improvement on the precision of the present world average. After full analysis we expect the eventual combined error on \( \delta \) to approach ±0.003.

3.1.5 Limits on \( S, P \), and \( T \) couplings.

A recent analysis was carried out by Mursula, Roos, and Scheck, who considered the more physical lepton-flavor-conserving, charge-changing interactions described by

\[ H = \frac{G_F}{\sqrt{2}} \sum_i \left\{ \bar{\nu} \Gamma_\mu \nu \right\} \left[ G_i \nu_\mu \Gamma_\mu \nu + G_i' \nu_\mu \Gamma_\mu \nu \right] + h.c., \quad (3.7) \]

where \( i = S, P, V, A, \) or \( T \). The analysis is made more physical through the introduction of certain simplifying assumptions. For example, in one analysis of \( T \) couplings, the authors assumed \( e\mu \) universality, that there are no \( S \) or \( P \) couplings, and that there is only one charged boson per coupling. They obtained the limit

\[ (|G_T|^2 + |G_T'|^2)^{1/2} \leq 0.2 \quad (1\sigma). \quad (3.8) \]

\( G_S \) and \( G_P \) are constrained by the \( \pi \rightarrow e\nu \) branching ratio to be \( \leq 10^{-6} \), unless some other suppression mechanism is invoked, e.g. Higgs-like coupling to lepton masses. In that event the analyses are more complex, leading to limits of order 0.2.

Since that analysis, the strongest new experimental constraints have come from the Berkeley-Northwestern-TRIUMF measurement \(^{28}\) of \( \xi P, \delta/p \) (an order-of-magnitude improvement over the previous world average); from the Berkeley-Northwestern-TRIUMF measurement of \( \delta \) described above; and from the 1984 improvement in the ETH-SIN-Maniz measurement of the transverse \( e^+ \) polarization in \( \mu^+ \) decay. How will these new data affect the limits on \( S, P \), and \( T \) couplings? In some cases \( (S, P) \) the best limits come from the new channels measured \( \text{(modulo the } \pi \rightarrow e\nu \text{ constraint described above)} \). In other cases \( (T) \) the best limits come from old measurements \( \text{(e.g. the } \rho \text{ parameter)} \). There the new data are still important, as they reduce the correlated error coming from variation of the \( V, A \) mixture.

My general conclusion is that recent experimental progress justifies renewed efforts to fit the general form of the charged-current interaction. The experimental groups are ready to help in interpreting their data.

3.2 Constraints on a possible right-handed \( W \)

I shall discuss possible right-handed currents in the context of the left-right-symmetric gauge group \( U(1) \times SU(2)_L \times SU(2)_R \), about which much has been written. In general the \( W \) mass eigenstates \( W_1 \) and \( W_2 \) need not be the same
as the gauge bosons $W_L$ and $W_R$ that couple exclusively to left- and right-handed leptons:

$$
\begin{pmatrix}
W_1 \\
W_2
\end{pmatrix} = 
\begin{pmatrix}
\cos \zeta & \sin \zeta \\
-\sin \zeta & \cos \zeta
\end{pmatrix}
\begin{pmatrix}
W_L \\
W_R
\end{pmatrix}.
$$

(3.9)

Finite mixing angle $\zeta$ would imply the existence of right-handed coupling effects measurable at low energies, irrespective of right-handed neutrino masses or of the mass of $W_1$ itself. The latter conventionally is parameterized by the small ratio

$$
\alpha \equiv \frac{M^2(W_1)}{M^2(W_2)}.
$$

(3.10)

Thus $\zeta$ could be measurable even if $\alpha$ is imperceptibly different from zero, and vice versa. I shall not discuss the associated neutral gauge bosons $Z_1$ and $Z_2$, except to remind you that, in $U(1) \times SU(2)_L \times SU(2)_R$, $M(Z_2)$ is related to $M(W_2)$ by the same weak mixing angle that relates $M(Z_1)$ to $M(W_1)$.

In the following I shall first discuss the relevant experiments, and then the implications of various assumptions concerning the associated right-handed neutrino.

### 3.2.1 Experimental input constraining $\alpha$ and $\zeta$

**Polarization of $\mu^+$ produced by $\bar{\nu}$.** Last year the CHARM group published the final result of their measurement of the polarization of muons produced by antineutrino interactions upstream in the CDHS detector. For $\mu^+$ produced at an average $Q^2$ of 4 (GeV/c)$^2$, the best-fit polarization was

$$
P_{\mu^+} = 1.10 \pm 0.24.
$$

(3.11)

Agreement with the expectation from more precise measurements at lower $Q^2$ illustrates an important point. At least within the context of the left-right-symmetric model, the $Q^2$ near which the relative contributions of left- and right-handed currents begin to change is of order $M^2(W_1)$. By that criterion, virtually every present-day experiment is a low-energy experiment.

**$y$ distributions in $\bar{\nu}N$ and $\nu N$ scattering.** In an analysis published two years ago the CDHS group made use of the inequality

$$
\zeta^2 \leq \frac{\sigma(\bar{\nu}N) - (1-y)^2 \sigma(\nu N)}{\sigma(\nu N) - (1-y)^2 \sigma(\bar{\nu}N)}
$$

(3.12)

within the region $x > 0.5$ and $y > 0.66$, where the systematic error associated with the subtraction in the numerator is smallest. (Their analysis was carried to higher order in $\alpha$, $\zeta$, and $M_N/E_\nu$ than is the above expression.) This is a good example of progress in experimental physics — last decade's high-$y$ anomaly is this decade's precise constraint on deviations from the standard model! The CDHS result (displayed more exactly as a contour in Fig. 14) is
\[ |\xi| \leq 0.095 \text{ (90\% confidence)} \quad (3.13) \]

The limit is remarkable not so much for its (still respectable) precision as for its independence from any assumption concerning the associated right-handed neutrino, a subject to which I shall return.

**Endpoint decay rate of \( \mu^+ \) produced by \( \pi^+ \) decay at rest.** We turn now to the Berkeley-Northern-TRIUMF\(^{26}\) search for possible effects of a right-handed \( W \) near the \( e^+ \) spectrum endpoint opposite to the \( \mu^+ \) spin direction. The preliminary result of this study was published\(^{26}\) last year, and has been discussed extensively at earlier conferences. Here I shall mention only the bare facts needed to understand the experimental method.

- The \( \mu^+ \) beam at TRIUMF is derived from \( \pi^+ \) decay at rest near the surface of the \( \pi^+ \) production target. As far as I know, it is the most highly polarized charged particle beam anywhere.
- The \( \mu^+ \) beam is stopped in [non-depolarizing] pure metal foils, within an ambient magnetic field either ("B\(_\parallel\)") 1.1 Tesla along the \( \mu^+ \) polarization direction \( P_\mu \), or ("B\(_\perp\)") 70 or 120 gauss normal to \( P_\mu \).
- Decay positrons, emitted opposite to the original \( P_\mu \), are momentum-analyzed with \( \Delta p/p = 0.2\% \) rms.
- When \( B_\parallel \) is applied, \( (V-A) \) forces the positron rate to zero at the endpoint. Instead \( (V+A) \) would maximize the rate there.
- When \( B_\perp \) is applied, the muon spin rotates and \( \langle P_\mu \rangle = 0 \). \( (V-A) \) produces a maximal muon spin rotation (\( \mu \text{SR} \)) asymmetry in the decay \( e^+ \) rate.
- These points are illustrated by Figs. 9 through 11. Figures 9 and 10 show the muon decay time spectrum with \( B_\parallel \) and \( B_\perp \) applied, respectively. The muon lifetime corresponding to Fig. 9 is \( 2.215 \pm 0.004 \) (statistical) \( \mu \text{sec} \), with a fitted background of \( -0.1 \pm 5.0 \) events per bin. The \( \mu \text{SR} \) signature in Fig. 10 is similar to others that you may have seen, except that the high muon polarization and high positron energy \( (x > 0.88) \) produce such a large modulation that on a logarithmic plot the sinusoidal wiggles seem distorted. The amplitude of that modulation is itself a measure of the effects of possible right-handed currents, a subject to which I shall return.

Figures 11 (a) and (b) compare the spectra in \( x \) near the positron endpoint when either \( B_\perp \) or \( B_\parallel \) are applied. The effectively unpolarized spectrum in (a) shows a characteristic sharp edge, which we use to calibrate the spectrometer. That edge vanishes almost completely when in (b) the strong longitudinal field holds the muon spin nearly antiparallel to the positron direction. If you look carefully at the curve fit to Fig. 11(b), you will see a tiny remnant of that edge as a slight step very close to \( x=1 \). In principle that is the signature of a right-handed current, and is about a 15-standard-deviation effect. In fact most of that step is due to the fact that average \( \cos \theta = |\hat{P}_\mu \cdot \hat{p}_e| \approx 0.985 \) owing to finite angular acceptance of the spectrometer.

Since the incoming muon and outgoing positron angles are measured for
FIG. 9. Decay time spectrum of $\mu^+$ stopped in a 1.1 T longitudinal spin-holding field, measured by the Berkeley-Northwestern-TRIUMF group in their determination$^{28}$ of $\xi^P \delta/\rho$. 
FIG. 10. Same as Fig. 9 with the longitudinal magnetic field replaced by a 70-gauss spin-precessing transverse field.
FIG. 11. Distributions in reduced positron momentum with the $\mu^*$ spin (A) processed as in Fig. 10, and (B) held as in Fig. 9. The edge in (A) corresponds to a resolution with a gaussian part < 0.2% rms. The fits are described in the text.
each event, it is natural to plot the size of the fitted step vs. \( \cos \theta \). The fit actually measures the quantity

\[
(\xi P_{\mu} \delta / \rho) \cos \theta = [1 - 2(2\alpha^2 + 2\alpha\xi + \xi^2)] \cos \theta ,
\]

which is the ordinate in Fig. 12. The intercept at \( \cos \theta = 1 \) of the best-fit line with unit slope produced our preliminary result

\[
(\xi P_{\mu} \delta / \rho) = 0.9989 \pm 0.015 \text{ (stat)} \pm 0.018 \text{ (syst)} .
\]

To protect against the possibility of unknown sources of muon depolarization in the beam or stopping target we prefer to quote the limit

\[
(\xi P_{\mu} \delta / \rho) > 0.9959 \text{ (90\% confidence)} .
\]

With the foregoing as an introduction, what is new for this conference? Data collected in the second and third (last) runs of the experiment have been processed through the analysis. They reduce the statistical error in (3.15) to \( \pm 0.0009 \). The new analogue to Fig. 11 looks much the same, except for the smaller error bars. The main new feature is the correction for Coulomb scattering of the muon upstream of the stopping target, previously \( +0.0012 \pm 0.005 \). As a result of detailed Monte Carlo study we have uncovered correlations between the Coulomb scattering and angular acceptance that make the calculation of this correction somewhat more subtle. At present it seems that the Coulomb correction will be smaller than before. Work continues on finalizing the systematic corrections and errors.

\[\mu SR\] asymmetry of \( \mu^+ \) produced by \( \pi^+ \) decay at rest. The Berkeley-Northwestern-TRIUMF group\(^{26}\) has prepared a new result for this conference using the alternate (\( \mu SR \)) method of searching for the effects of right-handed currents mentioned above. When the muon lifetime is factored out of the time spectrum in Fig. 10 and the result is plotted on a linear scale, the sinusoidal modulation in Fig. 13 is obtained. As noted above, its amplitude would be reduced by a \((V+A)\) admixture. The modulation in Fig. 13 is incomplete, not only because of the above-mentioned angular acceptance effects, but also because data over the range \( 0.88 < x < 1 \) are included. Thus the sensitivity of the \( \mu SR \) method to various sources of systematic error is quite different from that of the (published) endpoint rate method: absence of a strong magnetic field near the stopping target simplifies the measurement of muon and positron angles, but the \( x \) scale must be precisely calibrated in order to correct for the fact that \( <x> < 1 \).

Close inspection of Fig. 13 reveals evidence for relaxation of the \( \mu SR \) asymmetry amplitude with increasing muon lifetime. Without the strong longitudinal spin-holding magnetic field, various pure metal-foil targets (Al, Cu, Au) that gave apparently identical results in the endpoint-rate-analysis method appear different in the \( \mu SR \) method. The \( \mu SR \) asymmetry in the Cu targets was systematically about 2\% lower than the others; that sample was dropped from the \( \mu SR \) analysis. While negligible in the Au target, a relaxation of about 30\% over the 9.6 \( \mu \text{sec} \) \( \mu^+ \) lifetime range was observed in the \( \mu SR \) amplitude for the Al targets. Accordingly we extrapolated all fitted asymmetries to \( \tau = 0 \) using a gaussian dependence of \( \mu SR \) amplitude on \( \tau \). (Functional forms with additional param-
FIG. 12. Fitted \((\xi P \frac{\delta}{\rho}) \cos \theta\) for data like those in Fig. 11 (B), divided into bins of \(\cos \theta\). \(\xi, \delta,\) and \(\rho\) are muon decay parameters, \(P_\mu\) is the polarization of a \(\mu^+\) from \(\pi^+\) decay at rest, and \(\pi-\theta\) is the angle between the \(\mu^+\) spin and the positron direction.
FIG. 13. Decay time spectrum of data like those in Fig. 10, with the muon lifetime factor removed. The amplitude of the modulation is a measure of the effect of possible right-handed currents.
eters tended to give stronger limits.)

The quantity fit in the $\mu$SR analysis again is essentially $\xi P_\mu \delta/\rho$: with our new determination of $\delta$ the error on this statement is unimportant. The result is

$$\xi P_\mu \delta/\rho = 0.9977 \pm 0.0019 \text{ (stat)} \pm 0.0012 \text{ (syst)} , \quad (3.17)$$

with the following sources of systematic error:

- $\mu^+ $ scattering $\pm 0.0004$
- $e^+ $ scattering $\pm 0.0004$
- $B_{//} $ nulling $\pm 0.0002$
- $\mu^+ $ lifetime $\pm 0.0002$
- external radiative corrections $\pm 0.0003$
- definition of $x = 1$ $\pm 0.0004$
- $P_e $ calibration $\pm 0.0008$
- $e^+ $ track fitting $\pm 0.0003$

Again because of unknown sources of depolarization we prefer to quote the limit

$$\xi P_\mu \delta/\rho > 0.9948 \text{ (90\% confidence)} . \quad (3.18)$$

While the precision is comparable to our previous result$^{28}$ the sources of systematic error are quite different. Agreement between the two methods adds to our confidence.

3.2.2 Summary of experiments relevant to $W_R$.  

Figure 14 displays the present experimental constraints on the $W$ mass-squared ratio $\alpha$ and mixing angle $\xi$. In every case the allowed region includes the standard-model point $\alpha = \xi = 0$. The tightest constraints come from the Berkeley-Northwestern-TRIUMF determinations of $\xi P_\mu \delta/\rho$ (the small bold contour is our combined limit); from the (as yet unpublished$^{32}$) $\beta$ asymmetry in $^{19}$Ne decay (short-dashed contours); and from the 1966 measurement$^{33}$ of the $\rho$ parameter in muon decay (solid lines). Other limits are obtained from measurement of the electron polarization in Gamow-Teller $\beta$ decay$^{34}$ (dot-dashed lines); from comparison of the Fermi and Gamow-Teller $\beta$ polarizations$^{35}$ (long-dashed contours); from measurement of $\xi P_\mu$ in muon decay within nuclear emulsion$^{36}$ (dots); and from the $y$ distribution in $\bar{\nu}N$ and $\nu N$ scattering (double lines).$^{31}$

3.2.3 Constraints on $W_R$: effect of assumptions on $\nu_R$.  

No assumptions on $\nu_R$. Without any assumption on the possible right-handed neutrino, there is only one significant experimental constraint: the CDHS limit on $\xi$ from the $y$ distributions in $\bar{\nu}N$ and $\nu N$ scattering, where no right-handed neutrino need be produced. In addition to the usual diagram, the CDHS measure-
FIG. 14. Experimental 90%-confidence limits on the $W_{L,R}$ mass-squared ratio $\alpha$ and mixing angle $\zeta$ describing possible right-handed charged currents. The allowed regions are those that include $\alpha = \zeta = 0$. The small bold contour is the combined result from the Berkeley-Northwestern-TRIUMF data illustrated in Figs. 9-13. Other bounds are described in the text.
ment probes the diagram in which a $W_1$ still is exchanged and the leptonic vertex still is left-handed, but (through sin $\xi$ mixing) the hadronic vertex is right-handed and exhibits the "wrong" dependence on $\gamma$. The situation is similar in the angular distribution of semileptonic $W_1$ decay, where the data now are relatively crude but can be expected to improve rapidly.

Potentially the $W_2$ mass ($\alpha$) could be constrained by a search for its direct production. If an experiment were sensitive to its hadronic decay channels, for example by reconstructing jet-jet invariant masses, no assumptions on the right-handed neutrino would be necessary. Unfortunately this is a difficult experimental signature even for the $W_1$.

Calculations of the $K_L-K_S$ mass difference likewise do not depend on the $\nu_R$ mass. If $W_2$ exchange contributes to the relevant matrix element, calculations of the type originally used to predict the charmed quark mass produce too large a mass difference. Using this fact, Beall, Bander, and Soni originally obtained the lower limit

$$M(W_2) \geq 1.6 \text{ TeV} .$$

(3.19)

Thereafter many others extended the calculation to include $t$ and $h^0$ diagrams, obtaining much weaker lower limits of order 200-300 GeV. Recently Gilman and Reno used experimental restrictions on quark mixing matrix elements to remove some of the freedom in the extended calculations, reaffirming the original bound. Still stronger limits may be calculable. There remains some model-dependence in this approach, particularly in the necessity to make assumptions about the right-handed quark mixing matrix.

$\nu_R$ is assumed to be a Majorana neutrino with mass $\geq 1$ TeV. Lacking charge and baryon number, the neutrino is the only fermion that could be its own anti-particle (the Majorana case). If so, lepton flavors, leptons, and $(B-L)$ could not be conserved. If the lightest right-handed neutrino is a Majorana neutrino with mass exceeding about 1 TeV, no new constraints (beyond those mentioned above) on $\alpha$ or $\xi$ appear to be available. Such a high mass is not unlikely. In the Yanagida - Gell-Mann/Ramond/Slansky mechanism for lepton mass generation,

$$M(\nu_L) M(\nu_R) \approx m^2(\text{quark}) ;$$

(3.20)

$M(\nu_R)$ could be as high as $10^{11} - 10^{15}$ GeV.

$\nu_R$ is assumed to be a Majorana neutrino with mass $\leq 1$ TeV and to mix with $\nu_L$. This assumption needs some elaboration. Define

$$\nu^{}_{eL} \equiv \sum_{j=1}^{2n} U_{ej} N_{jL} ; \quad \nu^{}_{eR} \equiv \sum_{j=1}^{2n} V_{ej} N_{jR} ,$$

(3.21)

with $\nu$ the weak-eigenstate neutrino, and $N$ the mass-eigenstate neutrino. The mixing assumption here is the assumption that
\[ \sum_j U_{e j} V_{e j} = O(1) \] 

(3.22)

I am told that this is not easy to achieve in many gauge models, where the mixing angle is of order \( m(\nu_L)/M(\nu_R) \).

With these assumptions the dominant experimental constraint is given by limits on neutrinoless double beta decay. For vanishing \( M(\nu_R) \), both \( \alpha \) and \( \xi \) in principle would be constrained to be less than a few \( \times 10^{-4} \) by the non-observation of the neutrinoless mode. Then the \( W_2 \) mass would be bounded below by \( \sim 10 \) TeV. Useful limits could still be obtained up to \( M(\nu_R) \sim 1 \) TeV.

\( \nu_R \) is assumed to be a Majorana neutrino with mass between 5-10 MeV and 50-100 GeV. In this case, \( \nu_R \) production by proton collisions with maximally polarized electrons at HERA may be able to make a unique contribution in this mass window, with sensitivity up to \( \sim 500 \) GeV in \( W_2 \) mass.

\( \nu_R \) is assumed to be a Majorana neutrino with mass below 5-10 MeV. The experimental consequences here are nearly the same as those of the Dirac case discussed below.

\( \nu_R \) is assumed to be a 4-component Dirac particle like \( e \) or \( \mu \). Then \( M \equiv m \), and lepton flavors, leptons, and \((B-L)\) may still be conserved. Here the low-energy experimental results are most relevant: If both the endpoint-rate and \( \mu \)SR-asymmetry results on \( \xi_\mu \delta/\rho \) from the Berkeley-Northwestern-TRIUMF experiment\(^{28} \) are combined, the 90%-confidence limits are

\[ M(W_R) > 470 \text{ GeV} \quad \text{[no } W_L-W_R \text{ mixing]} \; ; \] 

(3.23)

\[ M(W_R) > 400 \text{ GeV} \quad \text{[any } W_L-W_R \text{ mixing]} \] .

When combined with the limit on \( \xi \) from measurement of the \( \rho \) parameter in \( \mu \) decay,\(^{29} \) the mass limit for any mixing angle would rise slightly. The \( \rho \) parameter by itself restricts

\[ |\xi| \leq 0.035 \quad . \] 

(3.24)

It appears to me that much of the future progress on \( W_R \) limits (or discoveries!) will be centered upon direct production in hadron colliders, with relatively few assumptions about neutrinos necessary, and tremendous increases in available energy on the horizon; and also upon improved neutrinoless double beta decay experiments, with their enormous sensitivity.

It is a pleasure to thank the organizers for a beautifully planned conference amid these inspiring surroundings.
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