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NEW RESULTS ON WEAK INTERACTIONS - SUMMARY AND ASSESSMENT

L.M. Sehgal

III. Physikalisches Institut, Technische Hochschule, Physikzentrum,
5100 Aachen, F.R.G.

New results have been presented at this Conference that have been obtained from a variety of lepton-hadron processes (neutrino interactions, muon scattering, atomic parity violation and beam dump experiments). I shall attempt in this summary to place these results in the context of the general endeavour to probe and define the phenomenological properties of the weak interactions.

1. NEUTRAL CURRENTS

1.1 Weak-Electromagnetic Interference in μN Interactions

The NA4 experiment at CERN (BCDMS collaboration)¹⁾ has compared the inclusive cross section of μ^+ and μ^- on a Carbon target:

$$\mu^\pm C \rightarrow \mu^\pm X \quad . \quad (1)$$

It is found that

$$\sigma(\mu^+, \lambda) \neq \sigma(\mu^-, -\lambda) \quad (2)$$

where $\lambda(-\lambda)$ denote the polarizations of the $\mu^+(\mu^-)$ beams. The beams actually used were nearly left-handed μ^+ and nearly right-handed μ^- , with $|\lambda| = 0.8$ and $E_\mu \approx 200$ GeV. The asymmetry (2) is a violation of the one-photon exchange approximation, which demands equal μ^+ and μ^- cross sections, regardless of polarization.

A charge asymmetry of the type (2) can arise from two sources:

$$B = [\sigma(\mu^+) - \sigma(\mu^-)] / [\sigma(\mu^+) + \sigma(\mu^-)] = B_{\text{rad}} + B_{\text{weak}} \quad . \quad (3)$$

The first is a QED radiative correction that can be symbolically represented as

$$B_{\text{rad}} \sim \text{Re} \left(\begin{array}{c} \mu \quad \mu \\ \diagdown \quad \diagup \\ \gamma \\ \diagup \quad \diagdown \\ q \quad q \end{array} \cdot \begin{array}{c} \mu \quad \mu \\ \diagdown \quad \diagup \\ \gamma \quad \gamma \\ \diagup \quad \diagdown \\ q \quad q \end{array} + \dots \right)$$

while the second denotes a weak-electromagnetic interference effect

$$B_{\text{weak}} \sim \text{Re} \left(\begin{array}{c} \mu \quad \mu \\ \diagdown \quad \diagup \\ \text{Z} \\ \diagup \quad \diagdown \\ q \quad q \end{array} \cdot \begin{array}{c} \mu \quad \mu \\ \diagdown \quad \diagup \\ \gamma \\ \diagup \quad \diagdown \\ q \quad q \end{array} \right)$$

The radiative effect B_{rad} has been calculated by Bardin and Shumeiko.²⁾ The weak asymmetry B_{weak} depends on the neutral current interaction of muons and quarks. Writing the effective Lagrangian as

$$\mathcal{L}_{\text{eff}}(\mu q) = -\frac{G}{\sqrt{2}} \left[\bar{\mu} \gamma_{\alpha} \mu \{ \epsilon_{VV}(q) \bar{q} \gamma_{\alpha} q + \epsilon_{VA}(q) \bar{q} \gamma_{\alpha} \gamma_5 q \} \right. \\ \left. + \bar{\mu} \gamma_{\alpha} \gamma_5 \mu \{ \epsilon_{AV} \bar{q} \gamma_{\alpha} q + \epsilon_{AA}(q) \bar{q} \gamma_{\alpha} \gamma_5 q \} \right] \quad (4)$$

the weak asymmetry is

$$B_{\text{weak}} = K \left[|\lambda| \left\{ \frac{2}{3} \epsilon_{VA}(u) - \frac{1}{3} \epsilon_{VA}(d) \right\} - \left\{ \frac{2}{3} \epsilon_{AA}(u) - \frac{1}{3} \epsilon_{AA}(d) \right\} \right], \\ K = -(\sqrt{2} G/e^2) (9/5) \left[\frac{1 - (1-y)^2}{1 + (1-y)^2} Q^2 \right] \frac{q-\bar{q}}{q+\bar{q}} \quad (5)$$

The last factor in K is a dilution factor due to antiquarks, close to unity for the conditions of this experiment. One therefore expects B_{weak} to be proportional to the variable $w \equiv Q^2[1-(1-y)^2]/[1+(1-y)^2]$, a prediction borne out by the data. The slope of this variation yields the combination of weak interaction parameters

$$|\lambda| \left\{ \frac{2}{3} \epsilon_{VA}(u) - \frac{1}{3} \epsilon_{VA}(d) \right\} - \left\{ \frac{2}{3} \epsilon_{AA}(u) - \frac{1}{3} \epsilon_{AA}(d) \right\} = 0.45 \pm .11_{-0.07}^{+0.05} \quad (6)$$

with $|\lambda| = 0.8$. Note that the measured quantity is a linear combination of a parity-conserving and a parity-violating term. By contrast, the SLAC $\bar{e}D$ experiment³⁾ measured a purely parity-violating effect, summarized by⁴⁾

$$\left\{ \frac{2}{3} \epsilon_{AV}(u) - \frac{1}{3} \epsilon_{AV}(d) \right\} + 0.25 \left\{ \frac{2}{3} \epsilon_{VA}(u) - \frac{1}{3} \epsilon_{VA}(d) \right\} = -0.26 \pm .015 \quad (7)$$

The constraints (6) and (7) are illustrated in Figs. 1a and 1b.

In the standard $SU(2) \times U(1)$ theory, the parameters appearing in (6) have the values

$$\frac{2}{3} \epsilon_{VA}(u) - \frac{1}{3} \epsilon_{VA}(d) = -\frac{1}{2} + 2\sin^2\theta \\ \frac{2}{3} \epsilon_{AA}(u) - \frac{1}{3} \epsilon_{AA}(d) = -\frac{1}{2} \quad (8)$$

Fig. 1a: Constraints on weak muon-quark couplings imposed by charge asymmetry in μ^+ -Carbon scattering (BCDMS collaboration, Ref. 1).

Fig. 1b: Constraints on weak electron-quark couplings imposed by SLAC polarization asymmetry (Ref. 3).

Fig. 2: Constraint on electron-quark couplings imposed by parity violation measurement in Cesium (Ref. 5) and SLAC e^+D experiment (Ref. 3).

Fig. 3: Mixing parameters of the charmed quark derived from dimuon data (CDHS collaboration, Ref. 14).

The measured asymmetry determines

$$\sin^2\theta = 0.22 \pm .06^{+.05}_{-.04} \quad (9)$$

In a slightly more general context in which the μ_R^- is allowed to have a non-zero isospin $I_{3R}(\mu)$, the expressions in (7) are replaced by $-1/2 + I_{3R}(\mu) + 2\sin^2\theta$ and $-1/2 - I_{3R}(\mu)$ respectively. Taking $\sin^2\theta = 0.23$, the data give

$$I_{3R}(\mu) = 0.01 \pm 0.06^{+.04}_{-.03} \quad (10)$$

consistent with the standard assumption of right-handed singlets.

It is amusing to note that the weak parameters given in (8) coincide with the coupling constants C_V and C_A which occur in a completely different neutral current sector, namely $\nu_\mu e$ scattering. This is a reflection of the factorization property inherent in all single-Z models, combined with the specific quantum number assignment $I_{3L} = (\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, -\frac{1}{2})$ for (ν_μ, e, u, d) in the standard theory.

1.2 Parity Violation in Cs Atom

An experiment by Bouchiat et al.⁵⁾ has observed a parity-violating effect in the scattering of circularly polarized light from Cesium vapour. An interference effect is seen between a parity-violating amplitude E_1^{PV} and a known parity-conserving Stark-induced amplitude βE_0 , with the result

$$\text{Im}E_1^{PV}/\beta = -1.34 \pm .22 \pm .11 \text{ mV/cm} \quad (11)$$

This constitutes a striking 6σ effect with only 8% systematic uncertainty. The theoretical expectation for $\sin^2\theta = 0.219 \pm .014$ is stated to be $-1.73 \pm .07 \pm 10\%$, the last uncertainty being due to atomic physics. In terms of the parameters of the neutral current Lagrangian (4) the quantity measured is

$$Q_W = -2 \left[\epsilon_{AV}(u) (2Z+N) + \epsilon_{AV}(d) (Z+2N) \right] \quad (12)$$

My assessment of the above result is that $[Q_W]^{Cs} = -55.2 \pm 11.5$, yielding the constraint

$$\epsilon_{AV}(u) + 1.12 \epsilon_{AV}(d) = 0.147 \pm .031 \quad (13)$$

It is interesting to note that this combination is almost orthogonal to the one determined by the "intercept" measured in the SLAC $\vec{e}D$ experiment³⁾:

$$\left[2\epsilon_{AV}(u) - \epsilon_{AV}(d) \right] / 3 = 0.30 \pm .08 \quad (14)$$

The constraints (13) and (14) are illustrated in Fig. 2.

1.3 Results from Neutrino Physics

There has been refinement as well as diversification in the study of neutral currents in neutrino processes. Some of the new results are as follows.

(i) Diffractive ρ^0 Production. An experiment at FNAL⁶⁾ reports the observation of diffractive ρ^0 production by neutral currents: $\bar{\nu} + N \rightarrow \bar{\nu} + N + \rho^0$. Comparing with the charged current process $\bar{\nu} + N \rightarrow \mu^+ + N + \rho^-$, and using vector meson dominance, it is possible to determine the parameter ' α ' of the neutral hadron current⁴⁾:

$$\sigma(\bar{\nu}N \rightarrow \bar{\nu} \rho^0 N) / \sigma(\bar{\nu}N \rightarrow \mu^+ \rho^- N) = \frac{1}{2} \alpha^2 \quad . \quad (15)$$

The result is $\alpha = 0.44 \pm 0.18$. (Recall that in the standard model $\alpha = 1 - 2\sin^2\theta_c$.)

(ii) Coherent π^0 Production: The Aachen-Padova experiment has observed a signal for the coherent process $\nu_\mu + A1^{27} \rightarrow \nu_\mu + A1^{27} + \pi^0$.⁷⁾ This reaction is largely determined by the divergence of the axial isovector current, and so selectively determines the parameter β . A preliminary estimate yields

$$\beta = 1.3 \pm 0.67 \quad (16)$$

where the error includes a large uncertainty from theory. The result is compatible with the standard expectation $\beta = 1$.

(iii) Single π Production: A new analysis of old measurements of single pion production has been made by Fogli⁸⁾, with a view to extracting the isoscalar couplings γ and δ . The results are

$$\begin{aligned} \gamma &= -0.202 \begin{matrix} +0.077 \\ -0.123 \end{matrix} \\ \delta &= 0.07 \begin{matrix} +.103 \\ -.102 \end{matrix} \end{aligned} \quad (16)$$

to be compared with the standard prediction $\gamma = -2\sin^2\theta_c/3$, $\delta = 0$.

(iv) Inclusive Scattering off Protons and Neutrons: Recent experiments in deuterium bubble chambers have measured the cross section ratio σ^{NC}/σ^{CC} on protons and neutrons separately. The results, converted into the chiral couplings of u and d quarks, are

$\underline{u_L^2}$	$\underline{d_L^2}$		
$0.19 \pm .06$	$0.13 \pm .04$	(15', Ref. 9)	
$0.14 \pm .04$	$0.18 \pm .05$	(BEBC, Ref. 10) .	(17)

The standard theory prediction $|d_L| > |u_L|$ is not yet decisively demonstrated by the above measurements. The right-handed couplings u_R and d_R remain, as before, poorly resolved.

(v) Couplings of strange quarks: In a comparative study of the y -distribution of CC and NC interactions, the CHARM experiment¹¹⁾ has detected a contribution from the NC coupling of strange quarks present in the $s\bar{s}$ sea. The coupling strength, when referred to that of the d -quark is

$$(s_L^2 + s_R^2)/(d_L^2 + d_R^2) = 1.39 \pm 0.43 \quad (18)$$

consistent with GIM symmetry, which predicts unity.

(vi) Couplings of charmed quarks: The CDHS experiment has observed the diffractive process $\nu + N \rightarrow \nu + N + \psi$.¹²⁾ Comparing the cross section with that of $\mu + N \rightarrow \mu + N + \psi$, and assuming vector and axial vector currents to contribute with equal weight (as in the Z -gluon fusion model) one arrives at an estimate of the NC coupling strength of charmed quarks

$$(c_L^2 + c_R^2)/(u_L^2 + u_R^2) = 2.1 \pm 1.0 \quad , \quad (19)$$

compatible with unity. It remains to be understood why a fusion mechanism, involving the emission of a coloured quantum from the nucleus, should be relevant to a diffractive channel in which the target suffers little or no excitation.

(vii) Neutrino-Electron Scattering: A new measurement of the ratio of $\nu_\mu e$ and $\bar{\nu}_\mu e$ cross sections has been reported by the CHARM experiment.¹³⁾ This ratio delivers a value of $\sin^2\theta$ relatively free of normalization errors:

$$\sin^2\theta = 0.215 \pm .040 \text{ (stat.)} + 0.015 \text{ (syst.)} \quad . \quad (20)$$

Combined with the earlier measurement of $\sigma(\bar{\nu}_\mu e)$, the new result also gives a measure of the overall strength parameter ρ of the NC Lagrangian,

$$\rho = 1.12 \pm 0.12 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \quad (21)$$

in agreement with the value $\rho = 1$ in the standard model.

2. CHARGED CURRENTS

2.1 Quark Mixing Parameters from $\mu^+\mu^-$ data

The CDHS experiment has made a detailed study of ν - and $\bar{\nu}$ -induced $\mu^+\mu^-$ events originating from the production and decay of charmed particles.¹⁴⁾ The objective is to determine the strength of the $|\Delta C| = 1$ cross section and thereby deduce the quark mixing parameters U_{cd} and U_{cs} . In a world containing u, c, d, s quarks only,

these parameters would simply be $U_{cd} = \sin\theta_c$, $U_{cs} = \cos\theta_c$, θ_c being the Cabibbo angle; but given the existence of at least three quark doublets, these parameters must be considered unknown, subject only to the unitarity constraint

$$|U_{cd}|^2 + |U_{cs}|^2 + |U_{cb}|^2 + \dots = 1.$$

The inclusive cross sections for $(\bar{\nu}) + N \rightarrow \mu^- + \mu^+ + X$ at asymptotic energies, assuming complete acceptance, are

$$\begin{aligned} \frac{d\sigma(2\mu)}{dx dy} &= \frac{G^2_{ME}}{\pi} \left[|U_{cd}|^2 q + |U_{cs}|^2 q_s \right] B_\mu \\ \frac{d\bar{\sigma}(2\mu)}{dx dy} &= \frac{G^2_{ME}}{\pi} \left[|U_{cd}|^2 \bar{q} + |U_{cs}|^2 q_s \right] B_\mu \end{aligned} \quad (22)$$

where $q = x(u+d)$, $\bar{q} = x(\bar{u}+\bar{d})$, $q_s = x(2s)$, in familiar notation, and B_μ is the average branching ratio of the charmed particle mixture produced in these reactions. Comparing with the single muon cross sections

$$\begin{aligned} \frac{d\sigma(1\mu)}{dx dy} &= \frac{G^2_{ME}}{\pi} \left[(|U_{ud}|^2 + |U_{cd}|^2)q + (|U_{us}|^2 + |U_{cs}|^2)q_s + \bar{q}(1-y)^2 \right] \\ \frac{d\bar{\sigma}(1\mu)}{dx dy} &= \frac{G^2_{ME}}{\pi} \left[q(1-y)^2 + (|U_{ud}|^2 + |U_{cd}|^2)\bar{q} + (|U_{us}|^2 + |U_{cs}|^2)q_s \right] \end{aligned} \quad (23)$$

one can, in principle, determine U_{cd} and U_{cs} . In practice, this is achieved only after a careful correction of the dimuon cross sections for effects of threshold and acceptance.

Following this procedure, the CDHS experiment¹⁴⁾ finds

$$\begin{aligned} (i) \quad |U_{cd}| &= 0.24 \pm .03 \\ (ii) \quad |U_{cd}|/|U_{cs}| &= (0.33 \pm 0.03) \left[2S/(\bar{U} + \bar{D}) \right]^{1/2}. \end{aligned} \quad (24)$$

The latter result involves the ratio of strange to non-strange sea contributions to the nucleon momentum. A safe upper limit is $2S/(\bar{U} + \bar{D}) < 1$, while a rough lower limit $2S/(\bar{U} + \bar{D}) > 0.16$ is obtained by combining the CDHS measurement of $\bar{U} + \bar{D}$ with the NC y -distribution measured by CHARM.¹¹⁾ The resulting constraint is

$$0.12 < \left| \frac{U_{cd}}{U_{cs}} \right| < 0.36 \quad (25)$$

The allowed domain of U_{cd} and U_{cs} is illustrated in Fig. 3.

2.2 Limits on right-handed currents

The y -distribution of the reaction $\bar{\nu} + N \rightarrow \mu^+ + X$ has been analysed in the framework of a Lagrangian containing both V-A and V+A currents:

$$\mathcal{L}_{CC} = -(G/\sqrt{2}) \bar{\mu} \gamma_{\alpha} (1 + \gamma_5) \nu \left[J_{\alpha} (V-A) + \rho J_{\alpha} (V+A) \right] . \quad (26)$$

The CDHS experiment obtains the limit¹⁵⁾

$$\rho^2 < 0.009 . \quad (27)$$

Likewise, the chiral structure of the charmed current has been analysed by studying the y -distribution of $\mu^+ \mu^-$ events. Assuming the interaction to have the form

$$\mathcal{L}_{CC}^{\Delta C=1} = -(G/\sqrt{2}) \bar{\mu} \gamma_{\alpha} (1 + \gamma_5) \nu \left[g_L J_{\alpha}^{\Delta C=1} (V-A) + g_R J_{\alpha}^{\Delta C=1} (V+A) \right] , \quad (28)$$

two experiments have obtained the results

$$\begin{aligned} g_R^2 / (g_L^2 + g_R^2) &= 0.15 \pm 0.10 && (\text{CHARM, Ref. 16}) \\ &< 0.07 \text{ (95\% C.L.)} && (\text{CDHS, Ref. 14}) . \end{aligned} \quad (29)$$

3. SEARCHES FOR ANOMALOUS BEHAVIOUR

3.1 Flavour-Changing Neutral Currents

An experiment at FNAL (CCFRS collaboration)¹⁷⁾ has studied prompt μ production in a beam dump, and has searched for $\mu^+ \mu^+$ and $\mu^- \mu^-$ events among a sample of dimuons. At 90% confidence, an upper limit

$$\frac{\mu^- \mu^- + \mu^+ \mu^+}{\mu^- \mu^+} < 0.8\% \quad (30)$$

is obtained, which, if interpreted in terms of possible $D^0 - \bar{D}^0$ mixing gives

$$P(D^0 \rightarrow \bar{D}^0) < 4.4\% , \quad (31)$$

thus constraining a possible $\Delta C = 1$ neutral current.

3.2 Scalar Couplings

The possibility that scalar quanta play a role in weak interactions prompts a continued search for scalar couplings in lepton-hadron processes. One signature is a y^2 term in the y -distribution of neutrino reactions. The CHARM experiment¹¹⁾

reports limits

$$\begin{aligned} g_{S,P}^2/g_{V,A}^2 &< 0.06 \quad \text{for charged currents} \\ &< 0.03 \quad \text{for neutral currents} \end{aligned} \quad (95\% \text{ C.L.}) \quad (32)$$

Another limit may be obtained by noting that scalar NC interactions, which flip helicity, cannot contribute to weak-electromagnetic interference in electron-quark scattering but can affect neutrino-quark processes. The fact that

$$\langle \sin^2 \theta \rangle_{\nu q} \approx \langle \sin^2 \theta \rangle_{eq} \quad (33)$$

suggests that such couplings are small. Note that if $\langle \sin^2 \theta \rangle_{\nu q}$ is derived from a comparison of NC and CC reactions through a Paschos-Wolfenstein type relation¹⁸⁾

$$\frac{1}{2} - \langle \sin^2 \theta \rangle_{\nu q} = \frac{\sigma(\nu \rightarrow \nu) - \sigma(\bar{\nu} \rightarrow \bar{\nu})}{\sigma(\nu \rightarrow \mu^-) - \sigma(\bar{\nu} \rightarrow \mu^+)} \quad (34)$$

such a derivation is insensitive to the existence of scalar CC or NC couplings, since any scalar contributions cancel out in the numerator as well as denominator of (34).

3.3 e- μ Universality

The validity of e- μ universality in charm-decay has come under question¹⁹⁾ in connection with the CERN beam dump "puzzle", namely $e/\mu \simeq 0.6 \pm 0.2$. A new experiment at FNAL²⁰⁾ yields a ratio 1.0 ± 0.3 , compatible with universality. Any suggestion of a difference in the e- and μ -branching ratios of charmed particles must contend with the nearly equal rate (within 10%) of $\mu^- \mu^+$ and $\mu^- e^+$ events in neutrino interactions¹⁴⁾. Small departures of e/ μ from unity could arise from radiative corrections that produce differences in the ν_e and ν_μ spectra of charm decay products.

3.4 Composite Quarks?

One signature for composite quarks is a non-zero radius. Experiments on $e^+e^- \rightarrow q\bar{q}$ limit the electromagnetic radius to $R < (100 \text{ GeV})^{-1}$. Another manifestation could be that the weak charged current vertex is not $\gamma_\alpha(1 + \gamma_5)$ but $\gamma_\alpha(1 + g_A \gamma_5)$. It is natural to expect that this renormalisation of the axial coupling would be very small, i.e. $|1 - g_A| \approx m_q R \approx 10^{-4}$. However, a direct analysis of the charged current data yields only the weak constraint

$$\left| \frac{1 - g_a}{1 + g_a} \right| < 0.1 \quad (35)$$

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