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DETERMINATION OF THE WEAK NEUTRAL-CURRENT COUPLINGS*

L. F. Abbott and R. Michael Barnett
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

ABSTRACT

A model-independent analysis of new data provides, for the first time, a unique determination of the weak neutral-current couplings of u and d quarks. Data for exclusive pion production are a crucial new input in this analysis.

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Weak neutral-current interactions were first observed in neutrino deep-inelastic scattering[1,2] ($\nu N \rightarrow \nu X$, where $X \equiv$ anything) only five years ago. Since then, they have been observed in elastic neutrino-proton scattering[3,4] ($\nu p \rightarrow \nu p$), in neutrino-induced inclusive pion-production[5] ($\nu N \rightarrow \nu \pi X$), in neutrino-induced exclusive pion-production[6,7] ($\nu N \rightarrow \nu \pi N$), and in non-hadronic processes.

In this paper, the most recent data for all four types of hadronic neutrino experiments are combined to find strict, new limits (independent of models) on the neutral-current couplings of u and d quarks. We consider only vector and axial-vector currents having the usual properties under charge conjugation, and we neglect the small effects due to s, c and other heavy quarks. Since these are difficult experiments with significant backgrounds, we feel it is important to use, at a minimum, 90% confidence limits on all experimental results rather than just one standard deviation.

There have been many analyses[8-11] of neutral-current data. Among the new features of this work are: 1) the exclusive pion data are analyzed in detail and are found to be a crucial input, 2) the elastic cross-sections are "inverted" to give allowed coupling values (using very recent data[4]), and 3) our analysis uses high-energy deep-inelastic data[2] for which the parton-model assumptions should hold and for which the experimental efficiencies are high.

In the notation used here, u_L, d_L, u_R and d_R are the coefficients in the effective neutral-current coupling:

$$\mathscr{L} = \frac{G}{\sqrt{2}} \bar{\nu} \gamma_\mu (1+\gamma_5) \nu \Big[u_L \bar{u} \gamma_\mu (1+\gamma_5) u + u_R \bar{u} \gamma_\mu (1-\gamma_5) u + d_L \bar{d} \gamma_\mu (1+\gamma_5) d + d_R \bar{d} \gamma_\mu (1-\gamma_5) d \Big]$$

For example, in the Weinberg-Salam (WS) theory[12] with the Glashow-Iliopoulos-Maiani mechanism[13], one has $u_L = 1/2 - 2/3 \sin^2\theta_W$, etc. In Fig. 1, we will plot our results in the u_L-d_L and u_R-d_R coupling constant planes. Since the overall sign of the neutral current is always ambiguous, we will choose our sign convention by requiring u_L to be positive; this will restrict our consideration to the upper half of the u_L-d_L plane.

The data for deep-inelastic scattering determine the values of $u_L^2 + d_L^2$ and of $u_R^2 + d_R^2$, i.e. — the radii of circles in the u_L - d_L and u_R - d_R planes. With 90% confidence upper and lower limits, these circles become the annuli which are shown in Fig. 1. We use the data of Ref. 2 which give neutral-current to charged-current ratios of $R_\nu^{DI} = 0.295 \pm 0.01$ and $R_{\bar{\nu}}^{DI} = 0.34 \pm 0.03$. An assumption concerning the antiquark to quark ratio in the nucleon is required to calculate these radii; however, the results are quite insensitive for ratios in the range 0 to 20%.

Since the radii in the left and right planes are reasonably well-determined, one can now use the other data to obtain information about allowed values of the angles θ_L and θ_R where

$$\theta_L \equiv \arctan\,(u_L/d_L) \qquad \theta_R \equiv \arctan\,(u_R/d_R)$$

In Fig. 2 we will plot the allowed angular regions, choosing left and right radii of 0.52 and 0.22, respectively (but all allowed radii give similar results).

The elastic neutrino-proton scattering data[3] provide significant limitations on the allowed angular regions. Using the data of Ref. 3 (with $R_\nu^E = 0.15 \pm 0.03$ and $R_{\bar{\nu}}^E = 0.21 \pm 0.07$), only the region inside the dotted curve in Fig. 2 is allowed at the 90% confidence level.[14] Note that the value of θ_R is not well-determined (especially for $\theta_L \approx 135^\circ$). The q^2 dependence of the data does not impose any significant additional limits.

Further restrictions on the allowed angular regions are imposed by the exclusive pion-production data.[6] A method for analyzing neutrino-induced exclusive pion-production was pioneered by Adler.[8] We use the detailed pion-production model of Adler (described in the first two papers of Ref. 8) which includes non-resonant production, incorporates excitation of the $\Delta(1232)$ resonance, and satisfies current algebra constraints. This model is valid only for small values of W, the invariant mass of the pion-nucleon system. We require $W < 1.4$ GeV. The data are not available with this cut; however, we note three important points: 1) for each process, most of the data are below $W = 1.4$ GeV, 2) use of ratios reduces the effect of this cut, and 3) most importantly, examination of a selected sample of events plotted in Ref. 6 indicates that application of the cut would strengthen not weaken our conclusions. There is some uncertainty in the theoretical analysis from several sources.[15] As a result, we feel it is best to require consistency with the exclusive-pion-production data only within a factor of two (which is, in fact, far greater than the 90% confidence level). Nonetheless, these data remain a crucial feature of our analysis.

To restrict the allowed angular region (Fig. 2) with exclusive-pion-production data[6], we consider six neutral-current to charged-current cross-section ratios (the neutral-current channels are $\nu \rightarrow p\pi^o, n\pi^o, p\pi^-, n\pi^+$ and $\bar{\nu} \rightarrow N\pi^o, p\pi^-$). The observed neutral-current cross-sections tend to be rather large because of excitation of the $\Delta(1232)$ resonance. This indicates that isovector currents are favored over isoscalar currents, especially in the left plane. The region allowed by both the elastic and the exclusive-pion data is shown in Figs. 1 and 2 by shading with lines. The allowed values of θ_R are greatly reduced by consideration of exclusive-pion-production data. It can be seen in Fig. 2 that the allowed region is now fairly small; this is not as evident in Fig. 1, since left-right correlations are not exhibited there.

Another input is provided by analysis of the inclusive-pion-production data.[5] This analysis (discussed by Sehgal[10]) involves significant parton-model assumptions. Unfortunately the data[5] presently available are taken at very low energies where such assumptions might be questionable. However, by making this data the final input in our analysis, its role is clear. The regions allowed at the 90% confidence level by this data alone are shown in Figs. 1 and 2. While two regions (and a very small part of a third), shown in Fig. 2, are allowed by the conjunction of elastic and inclusive-pion data, the exclusive-pion data reduces the number to just one.

The region of neutral-current coupling-constant space allowed by these four types of neutrino experiments is the small region in Figs. 1 and 2 which has shading with both lines and dots. Now for the first time, the neutral-current couplings are uniquely determined and are:

$$u_L = 0.33 \pm 0.07 \qquad u_R = -0.18 \pm 0.06$$

$$d_L = -0.40 \pm 0.07 \qquad d_R = 0.0 \pm 0.11$$

where the errors are 90% confidence limits and an overall sign convention has been assumed. It is interesting to note that knowledge of these quark couplings allows one to directly test the electron's couplings with searches for parity violation in electron-nucleon interactions.

Our results are compared with the predictions of various gauge models of the weak and electromagnetic interactions in Fig. 3. The WS model with $\sin^2\theta_W$ between 0.22 and 0.30 is entirely consistent with the data. Furthermore, the m_Z to m_W ratio obtained with the minimal Higgs boson structure[12] is the only ratio which leads to consistency with the data. This confirmation by the data may not be proof of the validity of the model, but it certainly is a remarkable result. The predictions of three other SU(2) x U(1) gauge models [16] are also shown in Fig. 3. These models have the same values of u_L and d_L as the WS model, and choosing $\sin^2\theta_W = 0.3$, we plot the corresponding values in the right plane. The model labelled A has a $(u\ b)_R$ coupling, B has a $(t\ d)_R$ coupling, and C (vector) has both. Even if the m_Z to m_W ratio is changed, none of these models (and probably no other conventional SU(2) x U(1) model besides WS . is consistent with the data. Also shown are two SU(3) x U(1) models [17,18] which are ruled out by this data; models D and E have the u quark in a right-handed singlet[17] and triplet[18], respectively. The parameters of some SU(2) x SU(2) x U(1) models can be chosen to give results very similar to those of the WS model.

In conclusion, the values of the weak neutral-current couplings of u and d quarks are now uniquely determined, setting strict limits on the construction of gauge models.

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Figure Captions

1. The left (a) and right (b) coupling planes. Annular regions are allowed by deep-inelastic data. The region shaded with lines is allowed by deep-inelastic, elastic and exclusive-pion data. The regions shaded with dots are allowed by deep-inelastic and inclusive-pion data.

2. Allowed angles for the radii given in the text. The dotted curve indicates the area allowed by elastic data. The region shaded with lines is allowed by elastic and exclusive-pion data. The elliptical regions are allowed by inclusive-pion data. The area shaded with dots is the only region allowed by all data.

3. Various gauge models compared with the allowed coupling constant region. The line marks the WS model for values of $\sin^2\theta_W$ from 0.0 to 0.7. A, B and C indicate SU(2) x U(1) models [16], and D and E indicate SU(3) x U(1) models [17,18] described in the text. For E, u_L and d_L lie within the shaded region.

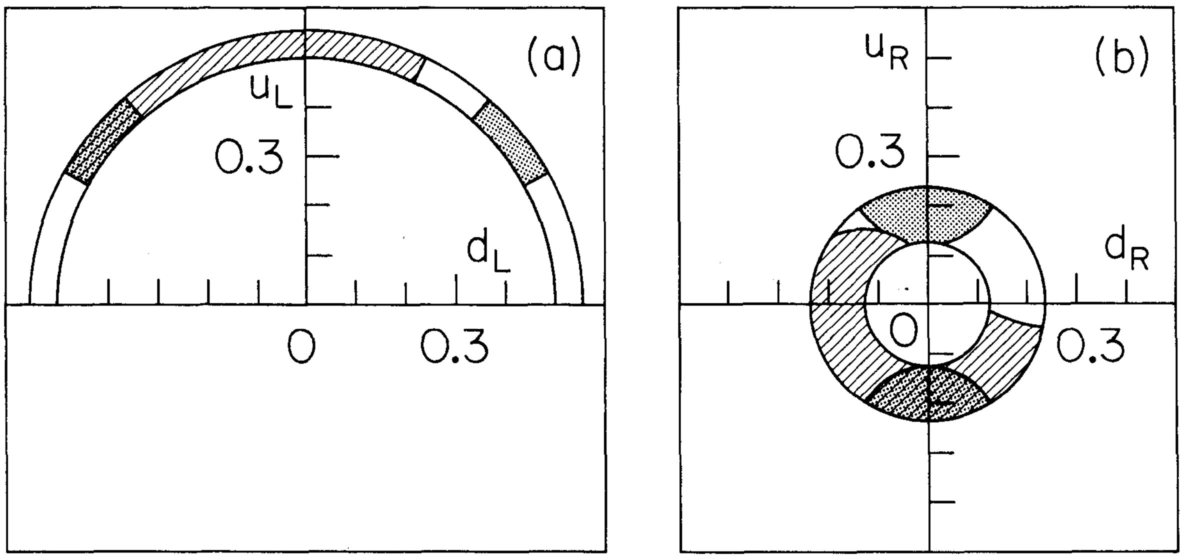

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Fig. 1

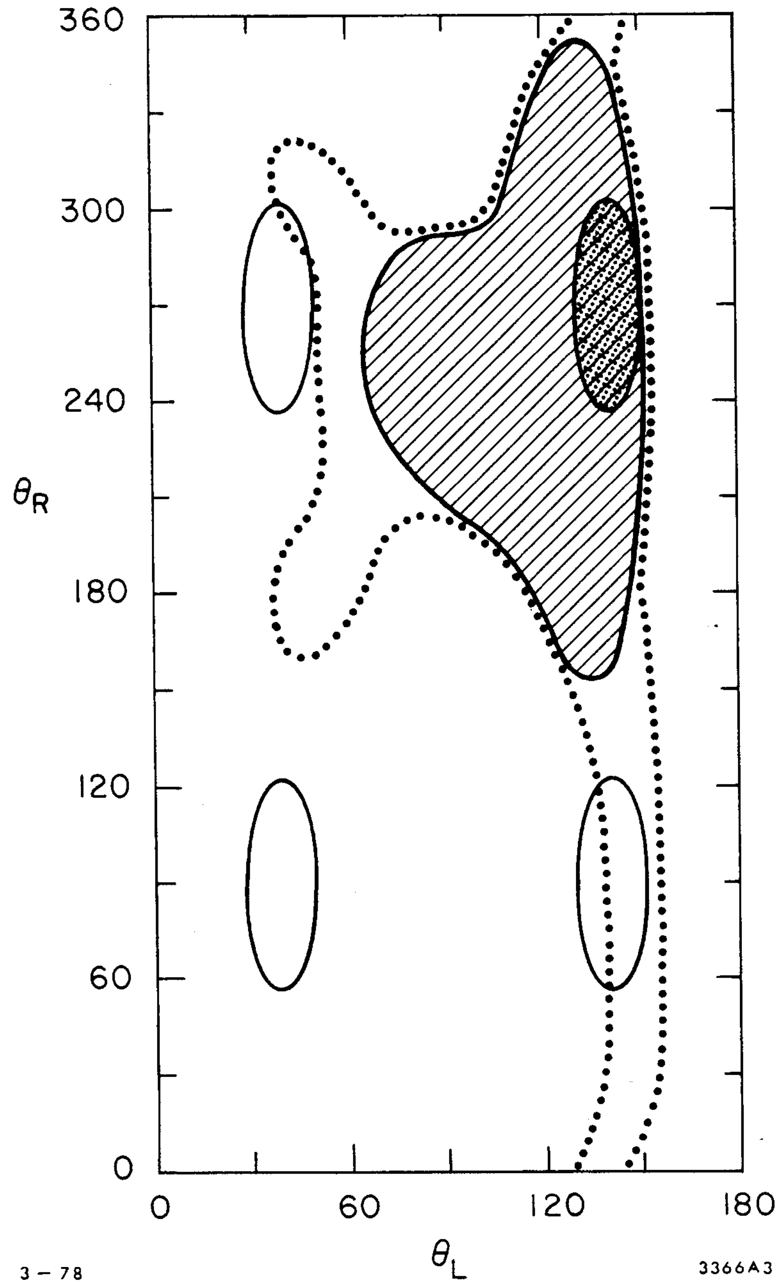

Fig. 2

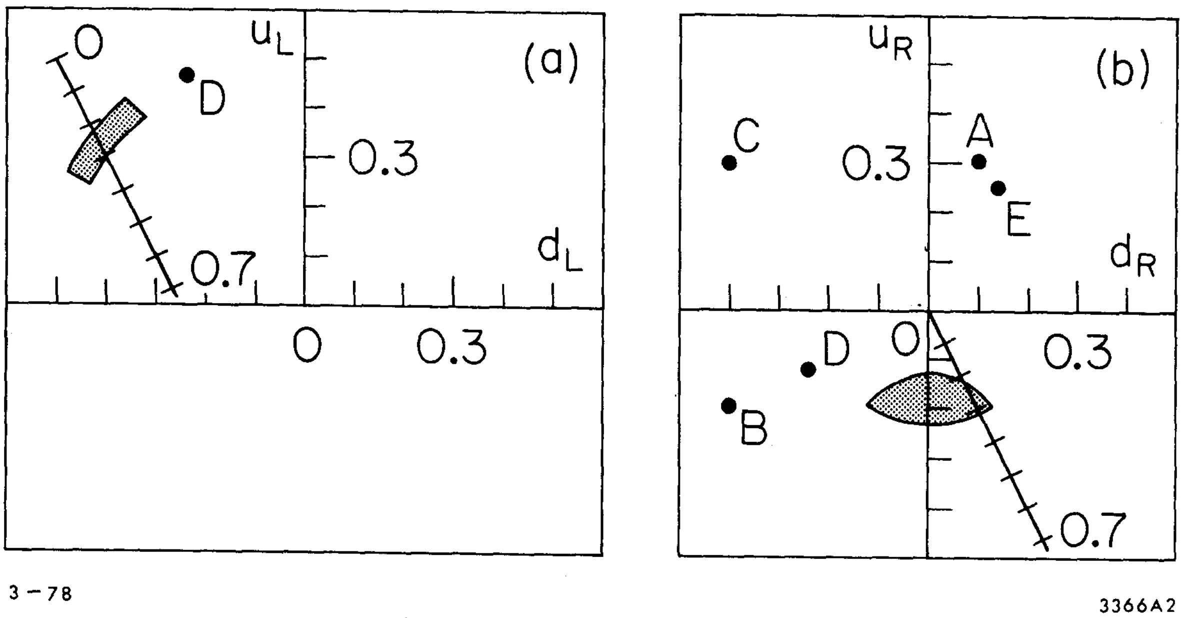

Fig. 3