Weak interactions and the baryonic current*

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We conjecture that neutrino scattering probes the baryonic currents of hadrons. A new model of $\Delta S=0$, $\Delta Q=0$ semileptonic weak interactions is constructed with numerous experimental consequences.

The hypothesis that the electromagnetic and weak interactions take advantage of currents that obey the symmetries of strong interactions is, without doubt, one of the few theoretical ideas in high-energy physics which has stood the test of time.[1] We know, for example, that low-q^2 semileptonic weak interactions directly measure the $1\pm i2$ component of the isospin in transitions such as $\pi^+\to\pi^0$ and $O^{14}\to N^{14}$ in exactly the same sense as low-q^2 photon interactions determine the electric charge of any object. Viewed in this way, it is somewhat disturbing that up to now—or at least until several weeks ago—the weak interactions have appeared not to exploit the baryonic charge or the baryonic current density, whose "measurability" has been contemplated from time to time by various theorists since the early days of elementary particle physics.[2] The purpose of this paper is to speculate on the possibility that the baryonic current, possibly together with its chiral partner, plays a major role in the semileptonic weak interactions and is in fact responsible for muonless events in high-energy neutrino collisions, recently reported by Hasert *et al.*[3] (Gargamelle collaboration) and by Benvenuti *et al.*[4] (Harvard-Pennsylvania-Wisconsin collaboration).

As is well known, there are now highly stringent limits on the interaction strength of strangeness-changing neutral currents based on $K_L\to\mu^+ +\mu^-$ and $K^+\to\mu^+ +\nu+\bar{\nu}$.[5] Conventional models of neutral currents utilize the third (and sometimes the eighth) component of the chiral F spin. In such models one must explain why there does not appear a Cabibbo-like linear combination, e.g., $\cos\theta' j_\mu^3+\sin\theta' j_\mu^6$, where θ' is the neutral-current analog of the Cabibbo angle; many attempts have been made to eliminate the unwanted $\Delta S=1$ pieces by various (artificial?) tricks.[6] Instead let us suppose that the only hadronic neutral current that appears in the weak interactions is the baryonic current ($I=0$, $C-$, $G-$), which in the quark model reads

$$j_\mu^{(B)}=i(\bar{u}\gamma_\mu u+\bar{d}\gamma_\mu d+\bar{s}\gamma_\mu s)\ , \tag{1}$$

possibly accompanied by its chiral partner

$$j_{5\mu}^{(B)}=i(\bar{u}\gamma_\mu\gamma_5 u+\bar{d}\gamma_\mu\gamma_5 d+\bar{s}\gamma_\mu\gamma_5 s)\ . \tag{2}$$

The neutral current (1) or (2) is a unitary singlet which remains invariant under generalized Cabibbo rotations of any kind, hence no unnatural mechanism is needed to eliminate strangeness-changing neutral currents.

Our basic assumption is that the baryonic current $j_\mu^{(B)}$ is coupled—either directly by Fermi coupling or by an intermediate neutral vector-boson coupling of the Yukawa type—to the neutral leptonic current which may take the form

$$j_\mu^{(L)}=i\,[\bar{e}\gamma_\mu(1+\gamma_5)e+\bar{\mu}\gamma_\mu(1+\gamma_5)\mu +\bar{\nu}\gamma_\mu(1+\gamma_5)\nu+\bar{\nu}'\gamma_\mu(1+\gamma_5)\nu']\ . \tag{3}$$

In addition, there may or may not be an analogous interaction of the axial baryonic current $j_{5\mu}^{(B)}$. We feel that we should have completely open minds on the chiral structure of neutral currents as long as we do not even understand the origin of parity violation in the charged-current weak interactions. Even the heretical possibility that the neutral *leptonic* current may lack $1+\gamma_5$ should not be dismissed *a priori*. Perhaps the whole of neutral-current phenomena just arises from the simplest conceivable parity-conserving coupling of the total "fermionic current"

$$j_\mu^{(F)}=i(\bar{e}\gamma_\mu e+\bar{\mu}\gamma_\mu\mu+\bar{\nu}\gamma_\mu\nu+\bar{\nu}'\gamma_\mu\nu' +\bar{u}\gamma_\mu u+\bar{d}\gamma_\mu d+\bar{s}\gamma_\mu s) \tag{4}$$

with itself.[7] Is it possible that it took forty years to uncover this most elegant aspect of "universal Fermi interactions?" But all this is highly speculative.

Turning now to specific reactions allowed by our model, let us first consider *truly elastic* scattering

$$\nu+p(n)\to\nu+p(n)\ , \tag{5}$$

where ν may stand for ν_e or $\nu_\mu(\nu')$. The vector part of this process explores the baryonic charge distribution of the nucleon in much the same way as electron-proton scattering as done by Hofstadter determines the electric charge distribution of the proton. The baryonic form factor measurable in this process should not be confused with the isoscalar form factor studied in elastic electron-nucleon scattering. In the language of vector-meson dominance supplemented by the standard quark-model mixing between ω and ϕ, we associate with the baryonic current the linear combination

$$V^{(B)} = -(\tfrac{1}{3})^{1/2}\phi + (\tfrac{2}{3})^{1/2}\omega \ , \tag{6}$$

while the isoscalar electromagnetic current (the hypercharge current) goes with

$$V^{(Y)} = (\tfrac{2}{3})^{1/2}\phi + (\tfrac{1}{3})^{1/2}\omega \ . \tag{7}$$

Single-pion production reactions

$$\nu + p \to \nu + \pi^+ + n \ , \tag{8a}$$

$$\nu + p \to \nu + \pi^0 + p \ , \tag{8b}$$

$$\nu + n \to \nu + \pi^- + p \ , \tag{8c}$$

$$\nu + n \to \nu + \pi^0 + n \ , \tag{8d}$$

provide extremely crucial tests of our model or of any model with an $I = 0$ neutral current. Since the baryonic current transforms like an isoscalar, Δ production with no extra pion is forbidden. We must have the final πN system in $I = \frac{1}{2}$ only, hence

$$\sigma(\pi^+ n) = \sigma(\pi^- p) = 2\sigma(\pi^0 p) = 2\sigma(\pi^0 n) \ . \tag{9}$$

Notice that the charged-to-neutral pion ratio is just the opposite (reciprocal) of what we would expect if the final πN system were due to pure Δ decay.[8] It is likely that Eq. (9) will be most cleanly tested in the neutrino experiment of the Argonne 12-ft. Bubble Chamber Group.[9]

$$\nu + p(n) \to \nu + \omega + p(n) \ . \tag{10}$$

In low-q^2, high-ν electroproduction, as well as in photoproduction, diffractive ω production is known to take place.[10] Since the ω-meson term appears in (6) as well as in (7), we expect neutrino-induced diffractive production of ω at least for low q^2 ($\lesssim 1$ GeV^2) at reasonably high values of ν, say $\nu \gtrsim 5$ GeV. It is amusing that sufficiently accurate data on ω and ϕ production by neutrinos, when compared to photo- and electroproduction, may actually throw light on the SU(3) structure of the neutral-current interactions. If the neutral current indeed transforms like a unitary singlet, the ratio of diffractively produced ω's to diffractively produced ϕ's is predicted by SU(3) to be larger than the corresponding ratio in electroproduction at the same values of q^2 by a factor of $\cot^4\theta$, where θ is the $\omega\phi$ mixing angle[11] ($\cot^4\theta = 4$ in the naive quark model). On the other hand, if the neutral current in the weak interactions were identical to the isoscalar electromagnetic current, the two ratios would, of course, be the same.

Let us now discuss deep-inelastic processes. If the axial-vector current $j_{5\mu}^{(B)}$ participates with full strength, it is reasonable to expect, just as observed in the charged current case,[12] sizable differences between the two inclusive reactions

$$\nu + p \to \nu + \text{any} \ , \tag{11a}$$

$$\bar{\nu} + n \to \bar{\nu} + \text{any} \ , \tag{11b}$$

and between

$$\nu + n \to \nu + \text{any} \ , \tag{11c}$$

$$\bar{\nu} + p \to \bar{\nu} + \text{any} \ , \tag{11d}$$

arising from VA interference. Because the $I = 1$ neutral current is postulated to be absent, we can derive naive charge-symmetry relations for (11a)–(11d) as follows:

$$\sigma(a)/\sigma(c) = 1 \ , \quad \sigma(b)/\sigma(d) = 1 \ . \tag{12}$$

If, on the other hand, the hadronic neutral current lacks $1 + \gamma_5$ so that the interaction is pure vector, the cross sections for all four processes are predicted to be equal and the y ($\equiv \nu/E$) distribution takes the form

$$\frac{dN}{dy} \propto [1 - y + \tfrac{1}{2}y^2/(1+R)] \tag{13}$$

for both neutrinos and antineutrinos, where R stands for the longitudinal-to-transverse ratio.

According to the Gargamelle collaboration[3] which studied

$$\nu_\mu + \text{“matter”} \to \nu_\mu + \text{any} \ , \tag{14a}$$

$$\bar{\nu}_\mu + \text{“matter”} \to \bar{\nu}_\mu + \text{any} \ , \tag{14b}$$

where "matter" is made up of approximately equal numbers of protons and neutrons, the cross sections for (14a) and (14b) are reported to be $(23 \pm 3)\%$ relative to $\nu_\mu \to \mu^-$ and $(46 \pm 9)\%$ relative to $\bar{\nu}_\mu \to \mu^+$, respectively. Since the ratio of $\bar{\nu}_\mu + \mu^+$ to $\nu_\mu \to \mu^-$ is known to be in the range 0.35–0.4, we note that the data are not inconsistent with the assumption of equal cross sections for (14a) and (14b), as expected from the pure vector hypothesis.

To proceed with our speculation we now consider the question of universality: Are the G's that appear in the charged and neutral current interactions "universal," and, if so, with what kind of Clebsch-Gordan coefficient? Write the vector part of the interaction as

$$(G\lambda/2^{1/2})[\bar{\nu}\gamma_\mu(1+\gamma_5)\nu + \cdots](\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d + \bar{s}\gamma_\mu s)$$
$$(G = 1.02 \times 10^{-5}/m_p^{\,2}) \ . \tag{15}$$

The most naive approach would be to take $\lambda = 1$, but other choices, of course, may appear more natural depending on how we classify leptons and hadrons.[13] In any case, if only the vector part participates, we can determine λ from elastic scattering as follows:

$$\left.\frac{(d\sigma/dq^2)(\nu+p\to\nu+p)}{(d\sigma/dq^2)(\nu_\mu+n\to\mu^-+p)}\right|_{q^2=0}=\frac{\lambda^2}{\cos^2\theta_C[1+(g_A/g_V)^2]}\,, \tag{16}$$

where θ_C is the Cabibbo angle. This relation is rigorous because at $q^2=0$ the vector part of the neutral-current interaction in our model is sensitive only to the baryonic charge of the proton. Because our baryonic current and the usual $\Delta S=0$ charged current are not related by SU(2) or by SU(3), it is in general not possible to obtain a model-independent absolute prediction for the ratio of neutral to charged current events in the deep-inelastic region. However, as a working hypothesis, it may be relatively safe to assume that if the charged-current events scale in the Bjorken manner,[14] so do the neutral-current events.

In comparing our model with other models such as the currently fashionable model of Weinberg, Salam, and Ward,[15] we admit that at this stage we have no ambitious program to "unify" the electromagnetic and weak interactions. On the other hand, the idea that high-energy neutrino scattering probes the baryonic current appears sufficiently intriguing and aesthetically pleasing that it may perhaps deserve as much attention as the more "orthodox" models of neutral currents. In any case the first task of the experimentalists in analyzing their muonless events should be to determine the symmetry properties—parity, isospin, SU(3) structure, etc.—of the newly discovered neutral current rather than to interpret the data using some particular version of unified and renormalizable gauge theories. It is hoped that our speculation, even if it may turn out to be false, will stimulate investigations on the neutral-current interactions *unhampered by theoretical prejudices*.

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[1]R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958); M. Gell-Mann, *ibid*. 125, 1067 (1962); N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963).

[2]E. P. Wigner, Proc. Natl. Acad. Sci. USA 38, 449 (1952); T. D. Lee and C. N. Yang, Phys. Rev. 98, 1501 (1955); J. J. Sakurai, Ann. Phys. (N.Y.) 11, 1 (1960).

[3]F. J. Hasert *et al.*, Phys. Lett. 46B, 138 (1973).

[4]A. Benvenuti *et al.* (unpublished).

[5]J. H. Klems, R. H. Hildebrand, and R. Stiening, Phys. Rev. D 4, 66 (1971); W. C. Carithers *et al.*, Phys. Rev. Lett. 30, 1336 (1973); *ibid*. 31, 1025 (1973).

[6]Rather than presenting an exhaustive list of references on this subject, we quote here Schwinger's view: "This has led to several suggestions, of varying degrees of charm, which are uniformly couched in the language of hypothetical subnuclear constituents. The number of the latter has thereby been increased, from three, to four, five, seven ..."; J. Schwinger, Phys. Rev. D 8, 960 (1973).

[7]Note that the intermediate boson version of this model is nothing more than massive quantum electrodynamics with the replacement, electric charge → fermionic charge.

[8]It is worth recalling in this connection the Columbia result

$$\frac{\sigma(\nu n\to\nu n\pi^0)+\sigma(\nu p\to\nu p\pi^0)}{2(\nu n\to\mu^- p\pi^0)}<0.14\quad(90\%\,\mathrm{CL}),$$

which, though not completely disastrous, is somewhat uncomfortable to Weinberg supporters [W. Lee, Phys. Lett. 40B, 423 (1972); B. W. Lee, *ibid*. 40B, 420 (1972)]. In our approach the numerator of this expression is due to an $I=\frac{1}{2}$ system decaying with an unfavorable Clebsch-Gordan coefficient, while the denominator is dominated by strong Δ production coupled with a favorable Clebsch-Gordan coefficient. So Lee's negative result is not too surprising.

[9]M. Derrick and P. A. Schreiner (private communication).

[10]See, e.g., K. C. Moffeit, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Bonn, 1973 (to be published).

[11]Unfortunately the actual situation is a little involved because of the large ω-ϕ mass difference. Detailed analysis on this subject may appear perhaps elsewhere.

[12]See, e.g., D. H. Perkins, in *Proceedings of the XVI International Conference on High Energy Physics, Chicago-Batavia, Ill., 1972,* edited by J. D. Jackson and A. Roberts (NAL, Batavia, Ill., 1973), Vol. 4, p. 189.

[13]This is somewhat analogous to the question of whether the W mass is determined by $e^2/m_W^2=2^{5/2}G$ or by $e^2/m_W^2=2^{3/2}G$. See, e.g., J. Schechter and Y. Ueda, Phys. Rev. D 2, 736 (1970); T. D. Lee, Phys. Rev. Lett. 26, 801 (1971); J. Schwinger, Phys. Rév. D 7, 908 (1973).

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[15]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam and J. C. Ward, Phys. Lett. 13, 168 (1964).