Manifest Left-Right Symmetry and its Experimental Consequences*

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We consider the possibility that weak interactions—in common with all other known interactions—do in fact enjoy a left-right symmetry manifest in the Hamiltonian, and that parity nonconservation stems from the spontaneous breakdown of this symmetry. We show that this picture is experimentally distinguishable from the conventional one in which parity nonconservation stems from the Hamiltonian. The implications of currently available experimental results are discussed and the need for new and decisive experiments is underlined.

Recent work on gauge theories of weak interactions has brought into focus the possibility that invariance under left-right conjugation is in fact a fundamental symmetry of nature, the symmetry realization being of the Nambu-Goldstone type rather than the more conventional Wigner-Weyl type.[1] The phenomenon of parity nonconservation, visible so clearly at all currently available energies, is then a consequence of the Nambu-Goldstone nature of the realization; in accordance with general discussions pertaining to the merger of symmetry realizations,[1] we expect freedom from parity nonconservation at very small distances.[2] The considerations presented below indicate that parity conservation may be largely restored at distances of the order of $(10^3\ \text{GeV})^{-1}$.

Our purpose in this note is to study the experimental consequences of *manifest* left-right symmetry in the charged-current sector. (By manifest left-right symmetry we mean that the physical left-handed and right-handed currents have identical transformation properties in flavor space,[3] and one current may be obtained from the other via $\gamma_5 \to -\gamma_5$). We have analyzed the constraints imposed on the parameters of such theories by all experiments done to date; these constraints are found to be mild enough to permit one to assert that the notion of spontaneously broken left-right symmetry may well be meaningful at low energies. Our work underlines the need for a systematic experimental investigation of left-right symmetry at currently available energies, as well as energies likely to be available in the foreseeable future.

For the purposes of this note, it is not necessary to commit oneself to any specific gauge model. To have a convenient framework for discussion, however, we shall abstract some features of a recently proposed $U(1)\otimes SU(2)_L\otimes SU(2)_R$ model[4] with four leptons (ν_μ, ν_e, μ, and e), and four quark flavors (u', u, s, and d).

We write the relevant part of the semiweak interaction in the form

$$\mathcal{L}_I = (g/\sqrt{8})[(V-A)_\rho W_L{}^\rho + (V+A)_\rho W_R{}^\rho + \text{H.c.}]. \tag{1}$$

Here W_L and W_R are positively charged fields and the currents displayed are charge-raising currents normalized in accordance with the Gell-Mann algebra.[5] Equation (1) embodies left-right symmetry in an obvious way.

The fields W_L and W_R are presumed to derive their masses from the Higgs mechanism.[5] It is remarkable, but true, that a completely symmetric Higgs potential can generate both a left-right-symmetric vacuum as well as an asymmetric vacuum.[6] We choose the asymmetric solution so that the right-handed gauge fields become more massive than the left-handed fields. In general, however, mixing effects will also set in and one has to diagonalize the mass matrix:

$$W_1 = W_L \cos\zeta - W_R \sin\zeta,$$
$$W_2 = W_L \sin\zeta + W_R \cos\zeta, \tag{2}$$

where $W_{1,2}$ are the mass eigenstates and ζ is a real mixing angle.

The effective interaction, operative at low frequencies, may be written in the form

$$-\mathcal{L}_{\rm eff} = (G/\sqrt{2})[V_\rho^+ V^\rho + \eta_{AA} A_\rho^+ A^\rho + \eta_{AV}(V_\rho^+ A^\rho + A_\rho^+ V^\rho)], \tag{3}$$

where

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8m_1^2}(\cos\zeta - \sin\zeta)^2 + \frac{g^2}{8m_2^2}(\cos\zeta + \sin\zeta)^2, \tag{4}$$

$$\eta_{AA} = (\epsilon^2 m_2^2 + m_1^2)/(\epsilon^2 m_1^2 + m_2^2), \tag{5}$$

$$\eta_{AV} = -\epsilon(m_2^2 - m_1^2)/(\epsilon^2 m_1^2 + m_2^2), \tag{6}$$

and

$$\epsilon \equiv (1 + \tan\zeta)/(1 - \tan\zeta). \tag{7}$$

Note that the $V-A$ limit corresponds to $\zeta \to 0$ and $m_2/m_1 \to \infty$.

We proceed to consider some of the experimental consequences of the interaction in Eq. (3). Only those processes which give clean and unambiguous information are listed.

(i) *Total rates for O^{14} β decay and μ decay.*—The usual formulas[7] for the rates continue to remain valid if one makes the identifications

$$G_\beta^V = G[\tfrac{1}{2}(1 + \eta_{AV}^2)\cos^2\theta]^{1/2}, \tag{8}$$

$$G_\mu = G[\tfrac{1}{4}(1 + \eta_{AA}^2 + 2\eta_{AV}^2)]^{1/2}, \tag{9}$$

θ being the Cabibbo angle [see remark (iv) below].

(ii) *Lepton polarization in semileptonic decays.*—We find

$$[P(l)_{\rm F}/P(l)_{\rm F}^{V-A}] = -2\eta_{AV}/(1 + \eta_{AV}^2), \tag{10}$$

$$[P(l)_{\rm GT}/P(l)_{\rm GT}^{V-A}] = -2(\eta_{AA}/\eta_{AV})[1 + (\eta_{AA}/\eta_{AV})^2]^{-1}, \tag{11}$$

where the suffixes F and GT mean transitions induced by the vector and axial-vector currents respectively (pure Fermi and pure Gamow-Teller, respectively, in the allowed approximation). Also, we have normalized our expressions for the polarization in terms of the standard results[7] derived in the $V-A$ limit.

(iii) *Spectrum in μ decay.*—The standard parameters,[8] ρ, δ, ξ, and η, which determine the spectrum, are related to the interaction parameters as follows:

$$\rho = \tfrac{3}{8}[(1 + \eta_{AA})^2 + 4\eta_{VA}^2]/[1 + \eta_{AA}^2 + 2\eta_{VA}^2], \tag{12}$$

$$\delta = \tfrac{3}{4}, \tag{13}$$

$$\xi = -2\eta_{VA}(1 + \eta_{AA})/[1 + \eta_{AA}^2 + 2\eta_{VA}^2], \tag{14}$$

$$\eta = 0, \tag{15}$$

$$P(e^\pm) = \pm\xi. \tag{16}$$

(iv) *Deep inelastic capture of polarized muons.*—To illustrate the onset of parity conservation at large momentum transfers, we retain the q^2 dependence of the W propagators in this process. For the differential cross sections we find

$$\frac{d\sigma(\mu_L) - d\sigma(\mu_R)}{d\sigma(\mu_L) + d\sigma(\mu_R)} = \frac{(m_2^2 - q^2)^2 - (m_1^2 - q^2)^2}{(m_2^2 - q^2)^2 + (m_1^2 - q^2)^2} + O(\zeta^2). \tag{17}$$

Here $\sigma(\mu_L) \equiv \sigma(\mu_L^+ P \to \nu_\mu + \ldots)$. Parity is exact in the limit $|q^2| \to \infty$; in this limit the ratio in Eq. (17) drops to zero.

TABLE I. Bounds on weak-interaction parameters.

Quantity	Lower bound	Upper bound	Experiment
$P(e)_{\rm F}/P(e)_{\rm F}^{V-A}$	0.939	1	0.97 ± 0.19 [a]
$P(e)_{\rm GT}/P(e)_{\rm GT}^{V-A}$	Input	1	1.001 ± 0.008 [b]
$P(e)_\mu/P(e)_\mu^{V-A}$	0.959	1	1.00 ± 0.13 [c]
$P(\mu)_\pi/P(\mu)_\pi^{V-A}$	0.985	1	1.1 ± 0.3 [d]
ρ	Input	1	0.752 ± 0.003 [c]
δ	0.750	0.750	0.755 ± 0.009 [c]
ξ	0.959	1	0.972 ± 0.013 [c]
η	0	0	-0.12 ± 0.21 [c]
m_2/m_1	2.76	∞	
$\tan\zeta$	-0.060	0.054	
η_{AA}	0.813	1.23	
$-\eta_{AV}$	0.698	1.11	

[a]H. Frauenfelder and R. Steffan, in *Alpha-, Beta-, Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965).
[b]J. Van Klinken, Nucl. Phys. 75, 145 (1966).
[c]T. G. Trippe *et al.*, Rev. Mod. Phys. 48, No. 2, Pt. 2, S51 (1976).
[d]M. Bardon *et al.*, Phys. Rev. Lett. 7, 23 (1961).

Remarks.—(i) We have listed, in Table I, lower and upper bounds as well as the best available experimental values for the various parameters mentioned above. The bounds were obtained by using as input the experimental values for the longitudinal electron polarization in pure Gamow-Teller β decay and the ρ parameter in μ decay. To achieve a high confidence level, we allowed for a spread of 2 standard deviations. In this paper we do not consider observables whose theoretical analysis involves in any way assumptions about the magnitude of SU(3) breaking.

(ii) Note that the mass of W_2, the gauge field with predominantly $V+A$ couplings, can be as low as 2.8 times the mass of W_1, the gauge field with predominantly $V-A$ couplings. In other words, whereas weak interactions at low energies in the charged-current sector are predominantly $V-A$, *$V+A$ interactions could well be present at a level of ~13% in the amplitudes.* If these interactions are firmly established by novel high-precision experiments, it would be natural to regard them as stemming from an underlying left-right symmetry of the Nambu-Goldstone genus.

With $m_1 \sim 60$ GeV, $m_2 \sim 170$ GeV, the $V+A$ interaction becomes 50% as important as the $V-A$ interaction in experiments which probe distances as small as $(147\ {\rm GeV})^{-1}$; at distances smaller than $(10^3\ {\rm GeV})^{-1}$, parity conservation is almost completely restored.

(iii) The neutron β-decay parameter commonly called $g_A(\equiv G_\beta^{A}/G_\beta^{V})$ is now replaced by two parameters—a g_A^{L} operative in the emission of right-handed $\bar{\nu}_e$, and a g_A^{R} operative in the emission of left-handed $\bar{\nu}_e$:

$$g_A^{L} = -(g_A)_{\rm AW}(\eta_{AA}-\eta_{VA})/(1-\eta_{VA}), \qquad (18)$$

$$g_A^{R} = +(g_A)_{\rm AW}(\eta_{AA}+\eta_{VA})/(1+\eta_{VA}), \qquad (19)$$

where $(g_A)_{\rm AW} \sim 1.2$ is the quantity calculated by Adler and Weisberger.[9]

(iv) Note that manifest left-right symmetry requires that the left Cabibbo angle *equal* the right Cabibbo angle[10] (modulo *finite* radiative corrections). Note further that while we can easily accommodate new leptonic and quark flavors, it is impossible to generate effective couplings of the form[11] $(G/\sqrt{2})\bar{\nu}_\mu\gamma_\rho(1-\gamma_5)\mu\cdot\bar{b}\gamma^\rho(1+\gamma_5)u$, b being the so-called bottom quark with charge $-\frac{1}{3}$. In our formulation, therefore, the high-y anomaly in deep inelastic $\bar{\nu}_\mu$-nucleon scattering and the rise in $\sigma(\bar{\nu}_\mu)/\sigma(\nu_\mu)$ with increasing energy[12] must be understood in terms of some other mechanism such as asymptotic freedom effects,[13] or sea effects[14] in the parton picture. These effects do account for the available[12] data within 2 standard deviations. More precise experiments could well rule out manifest left-right symmetry, or put it on firmer ground.

(v) It is evident that the most dramatic manifestations of left-right symmetry will be at very high energies.[15] The construction of the next generation of high-energy machines is eagerly awaited.

In the meantime, we hope that the precision of (a) polarization and asymmetry measurements, (b) deep inelastic ν_μ and $\bar{\nu}_\mu$ scattering experiments which probe the high-y region, and (c) experiments with polarized muon beams will be pushed as far as possible.

(vi) The imposition of manifest left-right symmetry (after appropriate enlargement of the gauge group) renders natural a model recently proposed for muon-number nonconservation.[16] This feature will be discussed elsewhere.

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Electric Neutrality of Matter

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With the use of a new feedback levitation electrometer (with an increase in sensitivity by 10^3 in comparison to our previous graphite experiments) iron objects of mass $\sim 2\times10^{-4}$ g have been explored for fractionally charged quarks and/or a possible electron-proton charge difference. Upper limits found were $N(\text{quarks})/N(\text{nucleons}) < 3\times10^{-21}$ and $(Q_p - |Q_e|)/Q_p < 10^{-21}$. The present "sensitivity" is $\sim 10^7$ times that of the original Millikan experiment.

A grain of matter (initially charged as always happens in practice) is ionized, adding or removing an appropriate number of electrons; will the (residual) charge of the grain become *exactly* zero? In this Letter we present results from the second stage of an experiment[1] aimed at answering the above question. Clearly, an affirmative answer implies that (a) the charges of electron and proton are exactly equal and opposite (if the neutron has zero charge); (b) the grain of matter does not contain any stable particle with fractional charge (e.g., an isolated stable quark with charge $\frac{1}{3}e$ or $\frac{2}{3}e$). Vice versa, any deviation from zero of the residual charge implies that the assumptions (a) and/or (b) are not fulfilled.

The interest in the experiment increases in