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BROKEN MIRROR (V ∓ A) *SYMMETRY OF THE WEAK INTERACTIONS OF ELEMENTARY PARTICLES AND THE PROPERTIES OF THE NEUTRINO*

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A new approach to the understanding of parity nonconservation in the weak interactions of elementary particles is proposed. Parity nonconservation is regarded as a manifestation of broken mirror (V ∓ A) symmetry which may be totally or partially restored in the limit of large values of the invariant momentum transfers. The restoration of the symmetry is explicitly realized in a model with intermediate vector bosons under conditions where perturbation theory holds. Possible experimental manifestations of broken (V ∓ A) symmetry of the weak interactions are discussed for various assumptions on the nature of the neutrino.

1. INTRODUCTION

AFTER the theoretical prediction[1] and the experimental observation[2] of parity nonconservation in the weak interactions of elementary particles, very important progress has been made in our knowledge of the properties of the latter with the discovery by Feynman and Gell-Mann,[3] Marshak and Sudarshan,[4] and Sakurai[5] of the (V − A)(V − A) scheme of the weak interactions and with the experimental verification of this scheme to good accuracy.[6]

However, the known question of Pauli why God (i.e., nature) has been left-handed in the weak interaction and also why parity is conserved in the strong and electromagnetic interactions, still remains open. On the other hand, the question of which is more fundamental (or "primary") in nature, conservation or nonconservation of parity, also has remained completely unresolved.

In the present paper a new formulation of the problem of the nonconservation of parity in the weak interactions of elementary particles is proposed, which apparently implies that parity conservation is more fundamental in nature.

We also discuss the possibilities of an experimental test of the consequences of the broken (V ∓ A) symmetry of the weak interactions at small energies, which together may give the possibility to solve the question whether one or two four-component neutrinos are the neutral partners of the electron and the muon in these interactions.

2. BROKEN (V ∓ A) SYMMETRY OF WEAK INTERACTIONS

Earlier,[7] a generalization of the current-current (V − A)(V − A) scheme of the weak interactions of elementary particles has been proposed[3-5] according to which the weak Lagrangian of weak interactions contains a (V − A)(V − A) as well as a (V + A)(V + A) coupling; however, the former dominates, at least in the region of small energies and momentum transfers:

$$L_w = \frac{G}{\sqrt{2}} j_\alpha^{(V-A)} j_\alpha^{(V-A)} + \frac{G_1}{\sqrt{2}} j_\alpha^{(V+A)} j_\alpha^{(V+A)}, \qquad (1)$$

where, by assumption,[3-5] all currents are charged. It was shown that despite the accuracy of the experimental data achieved at present, which in a number of cases reaches the order of one per cent, the upper limit for the ratio G_1/G is large:

$$|G_1 / G| \lesssim 0{,}1. \qquad (2)$$

Here we wish to emphasize with particular force that if the coupling between the currents of the weak interactions is in contrast to (1), effected by intermediate vector bosons,[3] then the proposed formulation of broken (V ∓ A) symmetry of the weak interactions takes on an important quality: this symmetry is restored in the limit of large values of the invariant four-momentum transfers. The situation here is analogous to that first observed in the case of broken isobaric symmetry of the weak and electromagnetic interactions of hadrons.[8] Moreover, no difficulties arise here connected with the account of virtual strong interactions, since it is entirely reasonable to assume that the essential consequences of parity nonconservation (in contrast to isospin breaking) should manifest themselves already in the consideration of the lepton processes alone.

In a model with intermediate bosons, we find, instead of (1), the following effective current-current Lagrangian for the weak interactions of elementary particles in first order perturbation theory:

$$L_w = 4\pi g^2 [j_\alpha^{(V-A)} \Delta_{\alpha\beta}(M_1^2, q^2) j_\beta^{(V-A)} + j_\alpha^{(V+A)} \Delta_{\alpha\beta}(M_2^2, q^2) j_\beta^{(V+A)}], \qquad (3)$$

where g is the semi-weak interaction constant, and $\Delta_{\alpha\beta}(M^2, q^2)$ is the propagator of the vector boson with mass M:

$$\Delta_{\alpha\beta}(M^2, q^2) = (q^2 + M^2)^{-1}(\delta_{\alpha\beta} + q_\alpha q_\beta / M^2), \qquad (4)$$

q_α is the four-vector of the momentum transfer. It follows from (2) that

$$M_2 \gtrsim 3M_1. \qquad (5)$$

Writing

$$j_\alpha^{(V\pm A)} \equiv j_\alpha^{(V)} \pm j_\alpha^{(A)}, \qquad (6)$$

we transform (3) to the following form:

$$L_w = 4\pi g^2[(j_\alpha^{(V)}j_\beta^{(V)} + j_\alpha^{(A)}j_\beta^{(A)})\Delta_1^{\alpha\beta}(M_1^2, M_2^2, q^2)$$
$$- (j_\alpha^{(V)}j_\beta^{(A)} + j_\alpha^{(A)}j_\beta^{(V)})\Delta_2^{\alpha\beta}(M_1^2, M_2^2, q^2)], \quad (7)$$

where $\Delta_1^{\alpha\beta}(M_1^2, M_2^2, q^2)$ and $\Delta_2^{\alpha\beta}(M_1^2, M_2^2, q^2)$ are the "effective" propagators[8] for the P even and P odd amplitudes of the weak processes:

$$\Delta_{1,2}^{\alpha\beta}(M_1^2, M_2^2, q^2) = \Delta_{\alpha\beta}(M_1^2, q^2) \pm \Delta_{\alpha\beta}(M_2^2, q^2). \quad (8)$$

In considering processes involving leptons (leptonic or semi-leptonic), one can confidently neglect terms with $q_\alpha q_\beta$ in the propagators of the intermediate bosons (4) and (8), at least in the region where perturbation theory holds. In the limit of large values of the invariant squares of the momentum transfers $q^2 > M_2^2$ the effective propagators (8) are in order of magnitude equal to

$$\Delta_1^{\alpha\beta} \approx \frac{2}{q^2}(\delta_{\alpha\beta}), \quad \Delta_2^{\alpha\beta} \approx -\frac{(M_2^2 - M_1^2)}{q^4}(\delta_{\alpha\beta}). \quad (9)$$

Therefore, the ratio of the P odd parts of the amplitudes for weak processes over the corresponding P even parts is in this limit equal to

$$(M_2^2 - M_1^2) / 2q^2 \ll 1, \quad (10)$$

i.e., in this region of momentum transfers parity conservation is restored explicitly if only the condition $q^2 > M_2^2$ is consistent with the applicability of first order perturbation theory for the weak interactions, $q^2 < (1000 \text{ BeV})^2$. This implies

$$M_2 \ll 1000 \text{ BeV}, \quad (11)$$

which is the condition for the applicability of the present considerations.

3. STRUCTURE OF THE LEPTON CURRENTS AND THE PROPERTIES OF THE NEUTRINO

The explicit form of the charged lepton (V ± A) currents depends essentially on the nature of the neutral partners of the electron and the muon, the neutrinos, which we shall regard as massless in the "absence" of weak interactions. From the condition of the restoration of parity conservation in the limit of large four-momentum transfers we find the following two possibilities:

1. One and the same four-component neutrino enters in all four lepton brackets:

$$(\bar{e}\gamma_\alpha(1 \pm \gamma_5)\nu), \quad (\bar{\mu}\gamma_\alpha(1 \pm \gamma_5)\tilde{\nu}), \quad (12)$$

where

$$\nu \equiv \nu_e + \tilde{\nu}_\mu, \quad \gamma_5\nu_e = \nu_e, \quad \gamma_5\tilde{\nu}_\mu = -\tilde{\nu}_\mu \quad (13)$$

and the sign ~ denotes the antiparticle. This possibility occurs only when there exists a lepton charge which has different signs for the electron and the muon.[9] Characteristic for this case is the specific effect of a "cross-jump" of the neutrino[8] ($\nu_e \longleftrightarrow \tilde{\nu}_\mu$, $\nu_\mu \longleftrightarrow \tilde{\nu}_e$) in the transition from the (V – A) to the (V + A) currents:

$$j_{l\alpha}^{(V-A)} = (\bar{e}\gamma_\alpha(1 + \gamma_5)\nu_e) + (\mu\gamma_\alpha(1 + \gamma_5)\nu_\mu), \quad (14)$$

$$j_{l\alpha}^{(V+A)} = (\bar{e}\gamma_\alpha(1 - \gamma_5)\tilde{\nu}_\mu) + (\bar{\mu}\gamma_\alpha(1 - \gamma_5)\tilde{\nu}_e), \quad (15)$$

and the connected effect of a possible interference of the (V – A)(V – A) and (V + A)(V + A) couplings entering in the weak Lagrangian. This leads to a number of interesting theoretical predictions of effects which can be experimentally observed in known weak processes, cf.[7,10] and below.

When the mirror symmetry of the weak interactions is completely restored, only the following vector (V) and axial vector lepton currents (A) will participate:

$$j_{l\alpha}^{(V)} = (\bar{e}\gamma_\alpha\nu) + (\bar{\mu}\gamma_\alpha\tilde{\nu}) \equiv (\bar{e}\gamma_\alpha\nu_e) + (\bar{e}\gamma_\alpha\tilde{\nu}_\mu) + (\bar{\mu}\gamma_\alpha\nu_\mu) + (\bar{\mu}\gamma_\alpha\tilde{\nu}_e), \quad (16)$$

$$j_{l\alpha}^{(A)} = (\bar{e}\gamma_\alpha\gamma_5\nu) + (\bar{\mu}\gamma_\alpha\gamma_5\tilde{\nu}) \equiv (\bar{e}\gamma_\alpha\nu_e) - (\bar{e}\gamma_\alpha\tilde{\nu}_\mu) + (\bar{\mu}\gamma_\alpha\nu_\mu) - (\bar{\mu}\gamma_\alpha\tilde{\nu}_e). \quad (17)$$

This possibility is at present the most economical.

In principle, the restoration of mirror symmetry at large momentum transfers q^2 could be tested experimentally, for example, in experiments on the annihilation of high-energy antiproton-neutron pairs into charged lepton pairs:

$$\tilde{p} + n \to e^- + \tilde{\nu}, \quad \mu^- + \nu. \quad (18)$$

The effect of the restoration of parity conservation should here lead to the vanishing of the longitudinal polarization of the electron and the muon and to the appearance in (18) of all four already known forms of the two-component neutrino ν_e, ν_μ, $\tilde{\nu}_e$, and $\tilde{\nu}_\mu$ in equal portions. We note by way of an example, that if the mass of the intermediate boson M is about equal to 2, 10, or 100 BeV, then this effect should be expected at the energy of colliding antiproton-neutron beams (or more realistically, colliding antiproton-deuteron beams) of the order of six, thirty, or 300 BeV in the c.m.s.[1)]

2. There exist two four-component neutrinos, the electronic, ν^e, and the muonic one, ν^μ, which enter in the (V ± A) brackets only together with the electron or with the muon,

$$(\bar{e}\gamma_\alpha(1 \pm \gamma_5)\nu^e), \quad (\bar{\mu}\gamma_\alpha(1 \pm \gamma_5)\nu^\mu). \quad (19)$$

This possibility occurs in the scheme with a single lepton charge as well as in the scheme with two lepton charges, electron and muon charge. In this case the characteristic interference mentioned above is absent, which can be essential for an experimental test.

When the mirror symmetry of weak interactions is completely restored in this case, then the following effective vector and axial vector lepton currents appear:

$$j_{l\alpha}^{(V)} = (\bar{e}\gamma_\alpha\nu^e) + (\bar{\mu}\gamma_\alpha\nu^\mu), \quad (20)$$

$$j_{l\alpha}^{(A)} = (\bar{e}\gamma_\alpha\gamma_5\nu^e) + (\bar{\mu}\gamma_\alpha\gamma_5\nu^\mu). \quad (21)$$

Hence, in contrast to case 1, when symmetry is restored (in particular, in the above-considered example of $\tilde{p}n$ annihilation) the polarization of e and μ vanishes here as before, but only the antineutrino states $\tilde{\nu}^e$ and $\tilde{\nu}^\mu$ appear, not the neutrino states ν^e and ν^μ.

[1)] It is interesting to note here that according to the model of a unified electromagnetic-weak interaction with heavy intermediate bosons,[8] the probability for antiproton-neutron annihilation into lepton pairs at about 100 Bev in the c.m.s. becomes comparable with the probability for antiproton-proton annihilation into photons.

4. SOME POSSIBILITIES OF AN EXPERIMENTAL TEST OF THE THEORY

The possible experimental consequences of the considered generalization of the (V − A)(V − A) scheme of the weak interactions of elementary particles at not very large energies can be divided into two groups.[2] The first group includes the general consequences of broken (V ∓ A) symmetry of the weak interactions which do not depend on the specific assumptions concerning the properties of the neutrino. In particular, these are the effects of the decrease of the asymmetry coefficients and of the longitudinal polarization of the electrons and muons in μ, β, and π decay, as compared with the predictions of the (V − A)(V − A) scheme. The corresponding formulas are given in[7]. We note that in this connection the data on the degree of longitudinal polarization P of the electrons in β decay are of considerable interest, which apparently speak in favor of $|P| < v/c$ and are in contradiction with the (V − A)(V − A) theory.[11] A further improvement of the accuracy of these experimental data on μ, π, and β decays is desirable.

The second group includes those consequences of the proposed (V ∓ A) theory of the weak interactions of elementary particles which depend essentially on the specific assumptions on the properties of the neutrino. These are the specific predictions of the theory in the model with a single lepton charge and one four-component neutrino[8] and also the possible interference of the (V − A)(V − A) and (V + A)(V + A) couplings. These consequences of the theory have been considered in detail in[7,10]. As was shown in[10], the most interesting consequence of the theory is in this case the nonvanishing value of the second Michel parameter η for the shape of the electronic μ decay spectrum at small energies, where the sign of the parameter η can be critical for the model with intermediate vector bosons. In addition, we mention two reactions which, as the reaction $\nu_\mu + p \rightarrow n + e^+$ discussed earlier, are of interest from the experimental point of view in connection with the experiments with high-energy neutrinos planned in Serpukhov:[12] the scattering of muonic neutrinos by electrons,

$$\nu_\mu + e \rightarrow \nu_\mu + e, \quad \tilde{\nu}_\mu + e \rightarrow \tilde{\nu}_\mu + e, \tag{22}$$

and the production of single strange particles in reactions of the type

$$\nu_\mu + p \rightarrow \Lambda + e^+. \tag{23}$$

The corresponding relative magnitude of the cross sections for these reactions is proportional to η^2, where $|\eta| \lesssim 0.1$.[10]

Of interest are also experimental attempts to observe the nuclear μ^- capture with emission of positrons, as proposed by Pontecorvo,[13] which is possible in our scheme in second order in the weak interaction, for example,

$$\mu^- + \Delta^{++} \rightarrow \nu_\mu + \Delta^+ \rightarrow e^+ + \Delta^0, \tag{24}$$

$$\mu^- + 2p \rightarrow \nu_\mu + pn \rightarrow e^+ + 2n \tag{25}$$

with a cross section proportional to $\eta^2 G^4$.

The experimental proof of $\eta \neq 0$ together with the observation of a single of the quadratic effects proportional to η^2 would unambiguously speak in favor of the (V + A)(V + A) coupling in the Lagrangian of the weak interactions in a model with a single four-component neutrino.

On the other hand, the experimental proof of the decrease of the values of the coefficients of asymmetry and of the longitudinal polarization of the electrons in μ and β decays and of the muons in π decay, as compared with the predictions of the (V − A)(V − A) theory, together with an indication that $\eta = 0$, would speak in favor of (V + A)(V + A) coupling in the weak Lagrangian but in a model with two different four-component neutrinos.

5. CONCLUDING REMARKS

1. In the (V ∓ A) theory considered, the neutrino has a mass of purely weak origin independently of any assumption on the number of lepton charges and four-component neutrinos. The "inclusion" of the weak interactions in both cases considered above leads to the appearance of a finite neutrino mass, which, apparently, is very small (smaller than or of the order of 10^{-7} eV for a momentum cut-off ≈ 1 BeV), since here there are no neutrino self-energy graphs with purely leptonic loops. However, in the case of two four-component neutrinos ν^e and ν^μ, their masses m_1 and m_2 must be different. As is easily seen from γ_5 invariance or by direct calculation (cf.[14]), their ratio is equal to

$$m_2 / m_1 = m_\mu / m_e \approx 207. \tag{26}$$

2. The proof of the correctness of the (V ∓ A) theory with two four-component neutrinos would apparently not yet imply unambiguously the existence of two lepton charges. In the case of a single lepton charge the two four-component neutrinos could also differ in properties of the "isobaric spin" type, which are connected with some internal symmetry group for the leptonic interactions.

3. The fundamental question whether one or two four-component neutrinos are involved as neutral partners of the electron and the muon in the weak interactions, cannot be resolved within the framework of an exact (V − A)(V − A) scheme of weak interactions.[3-5] This scheme also leaves completely open the other fundamental question, whether only one or two lepton charges exist, since the nonappearance of functions of one such charge may satisfy or duplicate the γ_5 invariance. However, these questions can in principle be answered if the (V − A)(V − A) scheme of weak interactions is only a first approximation to reality. The broken mirror (V ∓ A) symmetry of weak interactions is apparently the most natural and theoretically satisfying generalization.[3] It allows for a new approach to the understanding of the problem of the nonconservation of parity which possibly refers to

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[2] This subdivision was not made in [7].

[3] It is important to note that it is only in this generalization of the standard theory of weak interactions, that the pleasant property of the finiteness of the radiative corrections in μdecay is preserved and that the Michel parameter $\rho = 3/4$ remains unchanged.

the same range of phenomena as the broken symmetries in strong interactions. It has been shown in the present paper, at least for weak leptonic interactions in first order in the Fermi constant G in a model with intermediate bosons, that parity nonconservation in weak interactions can be regarded as a broken, but self-restoring left-right (V ∓ A) symmetry in the sense of the word as it was first formulated by Gell-Mann and Zachariasen.[15]

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