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A POSSIBLE THEORY OF WEAK INTERACTIONS

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ABSTRACT

A discussion is given of some of the recent experimental results in β-decay, and a possible theory of weak interactions is presented which is able to reproduce most of the results of the two-component theory but allows for the simultaneous presence of S and V in β-interaction without violating time reversal.

[+] This work was performed under the auspices of the United States Atomic Energy Commission.

[*] On leave of absence from Istituto di Fisica dell'Università di Roma, Italy.

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1 INTRODUCTION

Measurements of the angular distribution of the positrons emitted in the decay of oriented Co^{58}[1,2] give an asymmetry coefficient opposite in sign and about one third of that of Co^{60}. Such a value would be consistent with a negligible ratio $|M_F|/|M_{GT}|$ for the transition. However, with the value for such a ratio reported previously,[3] the asymmetry would be wrongly predicted if the β-decay interaction is assumed to consist mainly of T and S. A subsequent investigation of the $\beta^+ - \nu$ angular correlation in the decay of A^{35} -- for which M_{GT} appears to be much smaller than M_F[4] -- has led the author to the conclusion that V is the dominant Fermi coupling.[5] On the other

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1 Ambler, Hayward, Hoppes, Hudson, and Wu, Phys. Rev. 106, 1361 (1957).

2 Postma, Hiskamp, Miedma, Steenland, Tolhoek, and Gorter, Physica 23, 259 (1957).

3 D. F. Griffing and J. C. Wheatley, Phys. Rev. 104, 389 (1956).

4 Kistner, Schwarzschild, and Rustad, Phys. Rev. 104, 154 (1956).

5 Herrmannsfeldt, Maxson, Stahelin, and Allen (to be published).

+ This work was performed under the auspices of the United States Atomic Energy Commission.

* On leave of absence from Istituto di Fisica dell'Università di Roma, Italy.

hand, previous experiments on the $\beta^+ - \nu$ correlation in the decay of Ne^{19}[6] were all consistent with the absence of V but inconsistent with the absence of S. It is essential for such a conclusion to assume that T is the dominant Gamow-Teller coupling. If A were the dominant Gamow-Teller coupling, the N^{19} experiments could be interpreted as favoring V. However, the dominance of T in Gamow-Teller transitions is strongly indicated by the $\beta^- - \nu$ correlation in the decay of He^6.[7] The dominance of S is also indicated from the β decay of the neutron[8] -- again assuming the dominance of T.

In the general case of parity nonconservation, the conclusion that the assumption of time-reversal invariance, together with the absence (or smallness) of the Fierz terms, implies that either S or V is present but not both and -- similarly for A and T -- is no longer valid. However, such a conclusion again holds in a two-component neutrino theory ($C_j = \pm C'_j$, with the same choice of sign for all different couplings j).[9] Therefore the two-component theory of the neutrino would be inconsistent with the presence of both S and V in appreciable quantities, and/or of both T and A, unless time reversal is violated.

No direct experimental arguments in favor of or against time-reversal invariance have been reported so far. The only indirect

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[6] Maxson, Allen, and Jentschke, Phys. Rev. 97, 109 (1955); M. L. Good and E. J. Laner, Phys. Rev. 105, 213 (1957); and W. P. Alford and D. R. Hamilton, Phys. Rev. 105, 673 (1957).

[7] B. M. Rustad and S. L. Ruby, Phys. Rev. 97, 991 (1955).

[8] J. M. Robson, Phys. Rev. 100, 933 (1955).

[9] A. Salam, Nuovo Cimento 5, 299 (1957); L. D. Landau, Nuclear Physics 3, 127 (1957); and T. D. Lee and C. N. Yang, Phys. Rev. 105, 1671 (1957).

argument that has been presented is based on the large value found for the ratio of the lifetime of the long lived K^o to that of the short lived K^o.[10] The magnitude of this ratio finds a natural explanation in the assumption of time-reversal invariance. However, time-reversal invariance is not the only possible explanation of the large value of the ratio -- a possible smallness of the mass difference between the two K^o states would produce the same effect.[11] It has also been pointed out that the absence of 2π decay for the K^o long lived and a ratio of unity between the frequencies of decay of K^o long lived into e^+ and into e^- would both follow directly from the large ratio between the lifetimes.[12] Direct tests for testing time-reversal invariance in β-decay[13] and in $K \rightarrow \pi + \mu\ (e) + \nu$ decays[14] have been proposed.

At the present stage of experiments in β-decay, the possibility must always be left open that some of the experimental conclusions that have been drawn may be changed by later, more refined, experiments. However, if one wants to accept the present indication of the presence of both S and V, one can either conserve time reversal and abandon the two-component theory, or conserve the two-component theory and abandon time-reversal invariance, or, of course, abandon both. We do not consider the possibility of a complicated nonlocal structure of the

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10 R. Gatto, Phys. Rev. 106, 168 (1957).

11 Lee, Oehme, and Yang, Phys. Rev. 106, 340 (1957).

12 T. D. Lee, Proc. of the VII Rochester Conference, 1957 (to be published).

13 Jackson, Treiman, and Wyld, Phys. Rev. 106, 517 (1957) and M. Morita and R. S. Morita, Phys. Rev. 107, 139 (1957).

14 R. Gatto (to be published).

β-decay interaction essentially because it would not be expected to lead to appreciable modifications anyway since the wavelengths of the particles emitted in β-decay are large as compared to nuclear dimensions. We shall discuss here, as a possibility of retaining the hypothesis of time-reversal invariance, a four-component theory that has the advantage of preserving most of the successful predictions of the two-component theory and, at the same time, can explain most of the present data on β decay. In this theory, parity is violated in a definite way (different from the condition $C_j = \pm C'_j$ of the two-component theory) as a result of an invariance requisite imposed on the interaction Hamiltonian. This invariance requisite has been discussed by Nishijima as a possibility of obtaining further restrictions on the possible interaction Hamiltonians of the two-component theory.[15] We use it here alone, without requiring a two-component neutrino. The theory leads in μ decay to essentially the same conclusions of the Lee-Yang two-component theory. However, it allows for the presence in β decay of both S and V and of A and T without violating time reversal. It can be interpreted as a theory with two two-component neutrinos, one right-handed and one left-handed, in a way rather similar to a recent proposal by Mayer and Telegdi for β decay.[16] However, we are concerned rather with the whole class of neutrino interactions and not with β-decay only. Specifically, in β-decay the theory comes out to be essentially different from Mayer-Telegdi's theory, in the rule by which the two neutrinos are coupled in the β-decay interaction.

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[15] K. Nishijima, Nuovo Cimento 5, 1349 (1957).

[16] M. Goeppert Mayer and V. L. Telegdi (to be published).

2 μ-DECAY

The two-component theory, with lepton conservation, leads to a μ-decay spectrum with $\rho = 0.75$. The experiments seem to indicate a smaller value, $\rho = 0.68 \pm 0.02$.[17] The experiments also indicate an asymmetry parameter ξ with a magnitude $|\xi| = 0.87 \pm 0.12$,[18] which is rather near to the maximum possible value in the two-component theory, $|\xi| = 1$. Lee and Yang have recently proposed to explain the deviation of the experimental ρ value from the value 3/4 by assuming a nonlocal interaction for μ decay.[19] We shall take the viewpoint that both the deviation of from 3/4 and of $|\xi|$ from 1 are due to the same nonlocal effects, and we shall be concerned with a local approximation of the interaction Hamiltonian, for which ρ is exactly 3/4 and $|\xi|$ exactly 1.

Physically $|\xi| = 1$ means a definite spirality for the electron emitted in the μ decay. We take this indication as a starting point for postulating an invariance property of the interaction Hamiltonian under a transformation of the form

$$e \longrightarrow \exp\ (\ i\beta_e + i\alpha_e\gamma_5\ )\ e \qquad (1)$$

$$\mu \longrightarrow \exp\ (\ i\beta_\mu + i\alpha_\mu\gamma_5\ )\ \mu \qquad (1')$$

In (1) and (1') the factors exp ($i\beta$) correspond to the usual gauge transformation for charged fields, and they are introduced to compensate the phase factors arising from the factors exp ($i\alpha\gamma_5$).

Nishijima arrives at the invariance requirements (1) and (1') by noticing that the S matrix of quantum electrodynamics is left invariant

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[17] See K. Crowe, Bull. Am. Phys. Soc. 2, 206 (1957).

[18] Garwin, Lederman, and Weinrich, Phys. Rev. 105, 1415 (1957); J. Friedman and V. L. Telegdi, Phys. Rev. 105, 1681 (1957); and D. H. Wilkinson (to be published).

[19] T. D. Lee and C. N. Yang (to be published).

after such transformations.[20] However, if similar transformations were applied to the barion fields, they would change the S-matrix. This happens because of the opposite commutation properties of γ_μ and γ_5 with γ_5. If we assume that weak interactions are invariant under (1) and (1'), the total S matrix including weak interactions will be invariant under such transformations of the charged lepton fields.

We specify the two neutrino fields ν_1 and ν_2 by the conditions

$$\gamma_5 \nu_1 = \nu_1 \tag{2}$$

$$\gamma_5 \nu_2 = -\nu_2 \tag{2'}$$

and we assume lepton conservation.

Corresponding to our splitting of the neutrino field according to (2) and (2'), we write the most general Hamiltonian for a local approximation to μ decay in the form

$$H' = H'_{22} + H'_{12} + H'_{21} + H'_{11} + \text{Hermetian conjugate} \tag{3}$$

where

$$H'_{22} = \tfrac{1}{2} \sum_j G_j (\bar{e} \Gamma_j \mu)(\bar{\nu}_2 (1 + \gamma_5) \Gamma_j (1 - \gamma_5) \nu_2), \tag{4}$$

$$H'_{12} = \tfrac{1}{2} \sum_j F_j (\bar{e} \Gamma_j \mu)(\bar{\nu}_1 (1 - \gamma_5) \Gamma_j (1 - \gamma_5) \nu_2), \tag{4'}$$

$$H'_{21} = \tfrac{1}{2} \sum_j H_j (\bar{e} \Gamma_j \mu)(\bar{\nu}_2 (1 + \gamma_5) \Gamma_j (1 + \gamma_5) \nu_1), \text{ and} \tag{4''}$$

$$H'_{11} = \tfrac{1}{2} \sum_j L_j (\bar{e} \Gamma_j \mu)(\bar{\nu}_1 (1 - \gamma_5) \Gamma_j (1 + \gamma_5) \nu_1). \tag{4'''}$$

The G_j, F_j, H_j, L_j are the coupling constants for the different invariants Γ_j. The Hamiltonian H' is the most general parity-non-conserving Hamiltonian in a <u>four-component</u> theory without derivative couplings.

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20 This conclusion would not hold if couplings of the form $\sigma_{\mu\nu} F_{\mu\nu}$ were present (which do not satisfy the principle of minimal electromagnetic interaction).

In H'_{22} and H'_{11}, j can take only the values A and V. In H'_{12} and H'_{22}, j can take only the values S, T, and P.

Four different classes of Hamiltonians are found to satisfy the invariance requirements (1) and (1'). These are[21]

H'_{I} with $G_V = -G_A$, $F_j = H_j = 0$, $L_V = L_A$

H'_{II} with $G_V = G_A$, $F_j = H_j = 0$, $L_V = -L_A$

H'_{III} with $G_j = 0$, $F_S = -F_P$, $F_T = 0$, $H_S = H_P$, $L_j = 0$

H'_{IV} with $G_j = 0$, $F_S = F_P$, $H_S = -H_P$, $H_T = 0$, $L_j = 0$

H'_{I} is invariant under the transformations (1) if the phase factors β are chosen such that $\beta_e - \alpha_e = 0$, $\beta_\mu - \alpha_\mu = 0$; H'_{II} is invariant for $\beta_e + \alpha_e = 0$, $\beta_\mu + \alpha_\mu = 0$; H'_{III} for $\beta_e - \alpha_e = 0$, $\beta_\mu + \alpha_\mu = 0$; and H'_{IV} for $\beta_e + \alpha_e = 0$, $\beta_\mu - \alpha_\mu = 0$.[22]

The distribution in energy and angle of the electron emitted in $\mu^- \rightarrow e^- + \nu + \bar{\nu}$, with μ^- completely polarized, is given, in the approximation in which the electron mass is neglected, by

$$dN \sim \mathfrak{X}(1 - x) + 2\rho(4x - 3) + \cos\theta\left[-3\xi(1 - x) + \eta(4x - 3)\right] \qquad (5)$$

where x is the electron energy in unity of its maximum value in the decay, and θ is the angle with respect to the μ spin direction. The parameters ρ (Michel's parameter), ξ and η can be calculated for the four Hamiltonians satisfying our invariance requirement and are

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21 The result is perhaps more expressive for the ordering $(\bar{\mu}\nu)(\bar{e}\nu)$. One sees immediately, either directly or by a Fierz transformation, that the four classes of Hamiltonians are $(STP)_{11} + (VA)_{22}$, $(STP)_{22} + (VA)_{11}$, $(STP)_{21} + (VA)_{12}$, $(STP)_{12} + (VA)_{21}$, where we indicate, for instance, by $(STP)_1$ an expression of the form $\sum_{j=S,T,P} C_j(\bar{\mu}\Gamma_j(1+\gamma_5)\nu_1)(\bar{e}\Gamma_j(1+\gamma_5)\nu_1)$.

22 We are assuming that the α's for different leptons are unrelated.

found to be

for H'_I : $\rho = 3/4$, $\xi = -1$, $\eta = 3/2$

for H'_{II} : $\rho = 3/4$, $\xi = 1$, $\eta = -3/2$

for H'_{III} : $\rho = \dfrac{3|H_T|^2}{|F_S|^2 + |H_S|^2 + 3|H_T|^2}$, $\xi = -\dfrac{3(|F_S|^2+|H_S|^2) - 7|H_T|^2}{|F_S|^2+|H_S|^2+3|H_T|^2}$, $\eta = -2\rho$

for H'_{IV} : $\rho = \dfrac{3|F_T|^2}{|F_S|^2+|H_S|^2+3|F_T|^2}$, $\xi = \dfrac{3(|F_S|^2+|H_S|^2) - 7|F_T|^2}{|F_S|^2+|H_S|^2+3|F_T|^2}$, $\eta = 2\rho$.

The two-component theory with nonderivative coupling gives $\rho = 3/4$ and $\eta = -3/2\,\xi$. Therefore the distributions obtained from H'_I and H'_{II} are two particular cases of the distributions given by the two-component theory: the distribution obtained from H'_I is the same as that obtained from the two-component theory with the vector coupling constant equal but opposite in sign to the axial coupling constant; that obtained from H'_{II} is the same as that obtained from the two-component theory with the vector coupling constant equal to the axial coupling constant. The distributions obtained from H'_{III} and H'_{IV} become those of the two-component theory if the single condition $|F_S|^2+|H_S|^2 = |F_T|^2$, or $= |H_T|^2$, respectively, is satisfied, in which case both $\rho = 3/4$ and $\eta = -3/2\,\xi$. For proper choice of the parameters, H'_{III} and H'_{IV} can be made consistent with the experimental data. However, we prefer to consider the correct Hamiltonian to be H'_I or H'_{II}, because they both predict, without any further assumption, both ρ and ξ near to their experimental values. From the discussion of β-decay experiments, we shall derive that H'_{II} is the correct Hamiltonian.

For each of the Hamiltonians H'_I to H'_{IV}, the electron emitted in μ^- decay is completely polarized longitudinally--we are always using the approximation $m_e = 0$. In fact the electron is coupled in the combination $(1 - \gamma_5)e$ in H'_I and H'_{III}, and with $(1 + \gamma_5)e$ in H'_{II} and H'_{IV}. The polarization is independent from the μ polarization and has positive sign (spin parallel to the momentum, right-handed electron) for H'_I and H'_{III}, negative sign for H'_{II} and H'_{IV}.

As to the relation of the Hamiltonians H'_I and H'_{II} to the Lee-Yang Hamiltonians, it should be remarked that H'_I and H'_{II} are not equivalent to Lee-Yang Hamiltonians in the sense of the equivalence recently discussed by Pauli.[23,24,25] Moreover, a generalization of the Pursey-Pauli approach leads one to consider a transformation of the form (1), which also gives equivalent Hamiltonians for effects that do not depend on transverse polarization of the electron[25] as long as the electron mass is neglected. Again, even in this sense, H'_I and H'_{II} are nonequivalent to Lee-Yang Hamiltonians.

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23 N. Pauli, Nuovo Cimento 6, 204 (1957).

24 D. L. Pursey (to be published).

25 R. Gatto and G. Lüders (to be published).

3 β-DECAY

Imposing the invariance requirement (1) to the most general local β-decay Hamiltonians, one finds that the following two classes of Hamiltonians are admissible:

$$H''_{I} = \sum_{S,T,P} C_j(\bar{p}\Gamma_j n)(\bar{e}\Gamma_j(1+\gamma_5)\nu_1) + \sum_{V,A} C_j(\bar{p}\Gamma_j n)(\bar{e}\Gamma_j(1-\gamma_5)\nu_2)$$

$$H''_{II} = \sum_{S,T,P} C_j(\bar{p}\Gamma_j n)(\bar{e}\Gamma_j(1-\gamma_5)\nu_2) + \sum_{V,A} C_j(\bar{p}\Gamma_j n)(\bar{e}\Gamma_j(1+\gamma_5)\nu_1) \,.$$

H''_I is invariant if β_e is chosen such that $\beta_e - \alpha_e = 0$, and H''_{II} is invariant for $\beta_e + \alpha_e = 0$.

The first important point is that for both H''_I and H''_{II} the Fierz interference terms are always exactly zero. This can be easily derived from the observation that the Fierz terms, are interference terms between S and V, and between T and A. Summing over neutrino spins, one finds such interference terms contain factors of the form $(1 \pm \gamma_5)\Lambda_\nu(1 \pm \gamma_5)$ (where Λ_ν is the projection operator for the ν) which give zero.[26] This mechanism for the disappearance of the Fierz terms permits the existence in the β-decay interaction of both S and F and of both A and T.

The asymmetry parameter α for the angular distribution (written as $1 + \alpha \cos\theta$) of the electrons emitted from oriented nuclei in G.T transitions is, in the usual notations,

$$\alpha = \pm \frac{\langle J_Z \rangle}{J}\left(\frac{v}{c}\right)_e \lambda_{J',J} \qquad \text{for } H''_I \qquad (5)$$

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26 Mayer and Telegdi express this circumstance by saying that there can be no interference between left- and right-handed neutrinos.

and opposite for H''_{II}. The upper sign always refers to e^-, the lower to e^+. This result is independent from the values of the coupling constants C_T and C_A (both T and A may be present). The factor $\lambda_{J',J}$ only depends on the initial and final nuclear spins, J and J', and it is equal to one for the β^- decay of Co^{60}[27]. The result of this experiment is in agreement with the prediction from H''_{II}. This excludes H''_{II} as a possible Hamiltonian, and, as a consequence, H'_{I} is excluded for μ-decay, for which case the only possible Hamiltonian is now H'_{II}. We shall return later to a discussion of the π μ e cascade.

We note that, due to the automatic absence of the Fierz term in the present theory, the Rustad-Ruby experiment on He^6[7] can still be consistent with some fraction of A. The Co^{58} experiment[1,2] would require in our theory the smallness of a term

$$\mathrm{Re}(C_S C_T^* + C_V C_A^*)/(|C_T|^2 + |C_A|^2).$$

This can be obtained if there is an appreciable contribution from V and also a small contribution from A. The dominance of V over S, as indicated by the A^{35} experiment,[5] and the presence of a small A, would not be inconsistent with time-reversal invariance.

For both H''_{I} and H''_{II} the emitted electrons are polarized longitudinally. The polarization is, however, not complete, but of a magnitude (v/c), due to the mass term in the free-particle equation. Since the coupling is with $(1 - \gamma_5)e$ in H''_{I} and with $(1 + \gamma_5)e$ in H''_{II}, the emitted e^- is right-handed for H''_{I} and left-handed for H''_{II}. Therefore, for H''_{II} the theory predicts a longitudinal polarization = - (v/c) for e^- and + (v/c) for e^+, independent of the

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27 Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. 105, 413 (1957).

particular transition or of the values of the coupling constants. This is exactly the result that would hold in the usual two-component theory with a right-handed neutrino if V and A are absent. This result is consistent with all the results reported so far on G-T transitions. It is consistent with the recent results on the polarization of the positrons from Ga^{66} and Cl^{34}.[28] It is, however, inconsistent with the results reported previously on the longitudinal polarization of the electrons emitted from Ga^{66}[29] and from Sc^{46} and Au^{198}.[30] If these last results were confirmed, they would constitute a direct disproof of this theory.

4 $\pi \rightarrow \mu$ DECAY

In dealing with $\pi \rightarrow \mu + \nu$ decay, we use a phenomenological local Hamiltonian including first-order derivatives of the pion field. If the decay occurs through virtual barion-antibarion states coupled to the leptons by a Fermi-type interaction, one would expect nonlocal effects to be less important because the virtual intermediate states are very far from the energy shell. Two classes of Hamiltonians are invariant under (1'):

$$H'''_{I} = g\,(\bar{\mu}(1 - \gamma_5)\nu_2)\phi + i\,\frac{f}{m_\pi}\,(\bar{\mu}\gamma_\lambda(1 + \gamma_5)\nu_1)\,\frac{\partial \phi}{\partial x_\lambda}, \text{ and}$$

$$H'''_{II} = g\,(\bar{\mu}(1 + \gamma_5)\nu_1)\phi + i\,\frac{f}{m_\pi}\,(\bar{\mu}\gamma_\lambda(1 - \gamma_5)\nu_2)\,\frac{\partial \phi}{\partial x_\lambda}.$$

H'''_{I} is invariant for $\beta_\mu + \alpha_\mu = 0$, and H'''_{II} for $\beta_\mu - \alpha_\mu = 0$. The latter possibility would, however, be inconsistent with our result

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28 Deutsch, Gittelman, Bauer, Grodzins, and Sunyar (to be published).

29 Fraunfelder, Hanson, Levine, Rossi, and DePasquali (to be published).

30 Fraunfelder, Bobone, vonGoeler, Levine, Lewis, Peacock, Rossi, and DePasquali (to be published).

for μ decay, for which the only possible Hamiltonian was H'_{II}. Therefore, we are left with H'''_{I}.

In H'''_{I} the μ is coupled through $(1 + \gamma_5)\mu$; however, we cannot conclude from this that the μ^- in π^- decay is emitted left-handed, because of its low kinetic energy. Its longitudinal polarization is, rather, given by

$$P_L = \frac{-|g|^2 + |f|^2}{|g|^2 + |f|^2} , \qquad (6)$$

and it reaches the values ± 1 only if one of the two couplings is absent. We shall now show that the results on μ-decay imply that essentially only the derivative coupling exists. In the $\pi \to \mu \to e$ cascade, the measured value of ξ in the electron angular distribution is the product $P_L \xi$, where P_L is given by (6). The measured value of ξ is, however, very near to unity after accounting for depolarization effects in the medium, so that we are led to assume $|P_L| = 1$ in π-μ decay. On the other hand, the e^- from μ^- decay is known to be preferentially emitted backward with respect to the μ^- momentum. With our Hamiltonian H'_{II} the electron angular distribution with respect to the μ-spin direction is given by $1 - 1/3 \cos\theta$, which implies that electrons are preferentially emitted backward with respect to the μ-spin. Therefore the μ-spin is parallel to the momentum, which according to (6) implies derivative coupling. In the two-component theory with right-handed neutrinos and with lepton conservation the μ^- emitted in π^- decay must be left-handed, whereas in the present theory it must be right-handed. Moreover, the e^- emitted in μ^- decay is right-handed in the two-component theory with lepton conservation, but it is left-handed in the present theory. All these polarizations are reversed for opposite charge, as follows directly from the TCP theorem. A <u>direct</u>

measurement of such polarizations would permit us to decide between the present theory and the two-component theory with right-handed neutrinos.

A last remark concerns the absence of $\pi \rightarrow e + \nu$. It is gratifying at first sight to be able to conclude that the derivative coupling only is presumably effective in π decay, because, as it is well known, if one likes to assume that the coupling for π-e decay is the same as for π-μ decay, one finds a ratio of $\sim 10^{-4}$ for π-e decay to π-μ decay. The present upper limit for this ratio is, however, still smaller, $\sim 5 \times 10^{-5}$.[31] It might be that such a reduction is due to the other small effects that we have deliberately neglected--although such a possibility seems to us artificial. Moreover, it must be remarked that we have not been able to derive directly from the theory the conclusion that the coupling must be derivative, but we have only shown that this possibility is the most consistent with the $\pi \rightarrow \mu \rightarrow e$ experiments, if they are interpreted according to the theory here discussed.

Nishijima gives a theorem stating that weak interactions involving only a μ - e pair cannot be invariant under (1) and (1'), This theorem would forbid unwanted processes such as $K^0 \rightarrow \mu + e$, $K \rightarrow \pi + \mu^{\pm} + e^{\mp}$, $\mu \rightarrow e + \gamma$, $\mu \rightarrow e + e + e$, $\mu + N \rightarrow N + e$, etc. (which are not forbidden by lepton conservation under the present assignment, according to which μ^-, e^-, ν are leptons, and their charge conjugates antileptons). To prove such a theorem it is essential, however, to assume that the only sources of parity nonconservation are the couplings

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31 S. Lokanathan and J. Steinberger, Phys. Rev. 98, 240 (1955).

with the neutrino field. We do not see at present any reason for such a postulate.

5 FINAL REMARKS

It was the purpose of this work to show how a relatively simple theory can be constructed such that:

(i) It is based on general theoretical assumptions rather than on phenomenological hypotheses. Parity nonconservation arises from a postulated invariance property for the charged leptonic fields. The theory can be interpreted in terms of two massless two-component neutrino fields, and parity nonconservation is simply a reflection of the different way in which the two fields are coupled.

(ii) It maintains all successful predictions of the simpler two-component theory with right-handed neutrinos. It leads, moreover, to more specific predictions in μ-decay. It does not provide an explanation of the absence of $\pi \to e + \nu$, but it strongly suggests that the derivative coupling is responsible for such decay, thus leading to a very small transition probability. The philosophy underlying the theory is that some first approximation exists to the leptonic problems, such that leptons appear in the interactions as particles with definite spiralities. The deviations of ρ from 3/4 and of $|\xi|$ from 1 in μ decay would both be due to effects that are neglected in such local approximation to the interaction Hamiltonian.

(iii) It allows for the possibility of having both S and V, and, if necessary, both T and A in β-decay without implying violation of time-reversal invariance. It leads, for any mixture of couplings, to the same values for the longitudinal polarizations of

β-particles that are predicted by the two-component theory with right-handed neutrinos and with only S and T interactions. It is not consistent with all the β-decay experiments that have been reported in these last few months, but some of them appear in direct contradiction with each other.[32]

The theory discussed here is of course more complicated, and therefore less attractive, than a theory with one single two-component neutrino. We would conclude that a careful re-examination of the most relevant experimental results on β-decay has to be carried out before deciding on the two-component theory.

We may briefly examine two of the simplest possibilities. Suppose the conclusion from the He^6 experiment[7] is not valid, and that A instead of T is the predominant GT intersection. Then, from the β-decay of the neutron,[8] one would conclude that V is the dominant F interaction. This result would be confirmed by the Ne^{19} experiments,[6] and a direct experimental test would be the A^{35} experiment.[5] The Co^{60} experiment,[27] all the experiments carried out on the longitudinal polarization of β-particles in GT transitions, and the Ga^{66} and Cl^{34} experiments[28] would then indicate $C_A' = C_A$, $C_V' = C_V$. This theory would be a two-component theory with left-handed neutrinos. The Co^{58} experiment[1,2] would still present a difficulty, unless time-reversal invariance is not valid.

If, on the other hand, the He^6 result is valid and T is the dominant GT interaction, then, from the β-decay of the neutron one would conclude that S is the dominant F interaction. This result

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32 For a review of recent β-decay experiments, see T. Kotani, "Brief Review of Allowed β Transitions", UCRL-3798, May 1957.

would be confirmed by the Ne^{19} experiments, but the conclusion from the A^{35} experiment would be wrong. The Co^{60} experiment, the experiments on longitudinal polarization in GT transitions, and the Ga^{66} and Cl^{34} experiments would suggest $C_T' = -C_T$, $C_S' = -C_S$. This is the two-component theory with right-handed neutrinos. Again the Co^{58} experiment would constitute a difficulty if time reversal is valid.

The Rustad-Ruby experiment on He^6 is one of the most accurate experiments in β-decay. Its present role in deciding between the various theoretical possibilities is, however, so crucial, that we would strongly suggest a careful re-examination of the experimental conclusion in favor of tensor interaction in G-T transitions. If, on the other hand, further experimental evidence substantiates the present indication that none of the single solutions with a single two-component neutrino (either right- or left-handed) is able to explain β-decay, we would consider the theory discussed in this paper as a most attractive possibility for the description of weak interactions.

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