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Absence of $\mu-e$ Conversion Processes and the $\Delta I=\frac{1}{2}$ Rule*

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The lepton and strongly interacting particle currents in the universal Fermi interaction are both assumed to be split into two parts, even and odd, with respect to an internal symmetry operation. The requirement that the over-all interaction be even allows $2\mu\rightarrow 2e$ processes while forbidding single $\mu\rightarrow e$ conversion and requires that the nonleptonic decays come about through the coupling of the strangeness-changing current with itself. This leads us to a theory which differs from the schizon scheme by allowing $\Delta S=2$ leptonic processes, and differs from the veton scheme by associating electrons with muon neutrinos in strangeness-changing processes.

I. INTRODUCTION

THE history of the universal Fermi interaction is marked by the growing recognition of symmetry in the form of interaction, together with restrictions on the universality of the weak four-fermion interaction, as more has been learnt from the experimental data. These questions of symmetry and of universality are, in all likelihood, intimately related. The most striking restriction on the universality of the Fermi interactions is the apparent absence of interactions by which muons convert into electrons without the emission of neutrinos. The most striking symmetry appearing in the weak interactions is the $\Delta I=\frac{1}{2}$ rule for the change in isospin of strongly interacting particles. In this paper we attempt to relate these two outstanding problems in the theory of weak interactions.

The universal Fermi interaction theory applied in this paper is that according to which there exists a weak interaction,

$$\mathcal{L}_{\text{int}}=G\mathcal{J}_\mu\mathcal{J}_\mu^\dagger, \tag{1.1}$$

between currents

$$\mathcal{J}_\mu=j_\mu+J_\mu+S_\mu, \tag{1.2}$$

composed additively of a lepton part j_μ, a strangeness-preserving baryon part J_μ, and a strangeness-changing baryon part S_μ. J_μ and S_μ may contain strangeness-preserving and strangeness-changing boson terms as well, in order to express various conservation or partial-conservation laws that may obtain for the weak interaction currents.

In Sec. III we study the isospin and strangeness symmetry properties that J_μ and S_μ are expected to have in order to obtain the $\Delta I=\frac{1}{2}$ rule. First, however, we wish to consider the restrictions on the universality of the Fermi interactions that are imposed by the absence of $\mu-e$ conversion processes. In this next section we also consider the possibilities of intermediary mesons which, through Yukawa couplings to $\mathcal{J}_\mu$, could lead to (1.1) as an effective interaction.

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II. $\mu-e$ CONVERSION AND EVEN AND ODD LEPTON CURRENTS

A. Unwanted Leptonic Processes

The problem among the leptons is to forbid the occurrence of processes such as

$$\mu\rightarrow e+\gamma \quad\text{or}\quad e+e+e, \tag{2.1}$$

$$\mu+\text{nucleus}\rightarrow e+\text{nucleus}, \tag{2.2}$$

or

$$K,\pi,\gamma\rightarrow\mu+e \text{ (with or without pions)}, \tag{2.3}$$

in which muons and electrons would convert into each other singly or be produced in association. It is important to understand that the absence of these $\mu-e$ processes and the nonoccurrence of *like* lepton pairs $\nu\nu$, ee, or $\mu\mu$ in certain reactions pose rather independent problems. Any theory permitting only charge exchange for the lepton currents would automatically forbid the production of like leptons but could still allow $\mu\rightarrow e$. (Any charged-intermediary boson theory with one kind of neutrino is in this category.) On the other hand, a theory forbidding $\mu-e$ conversion could nevertheless, if neutral lepton currents are admitted, allow the production of like leptons. (A charge-symmetric theory with different μ and e neutrinos is in this category.) The logical independence of the like- and unlike-lepton problems must be appreciated; in this paper the nonoccurrence of $\mu-e$ conversions is used to suggest a theory in which, among other things, $\nu\nu$, $\mu\mu$, and ee are forbidden.

The evidence for the suppressions of $\mu-e$ transitions comes from the failure to observe events in which a muon changes into an electron with the emission of a momentum-conserving real or virtual photon. The branching ratios

$$(\mu\rightarrow e+\gamma)/(\mu\rightarrow e+\nu+\bar{\nu}),$$
$$(\mu+\text{“}p\text{”}\rightarrow e+\text{“}p\text{”})/(\mu+\text{“}p\text{”}\rightarrow\nu+\text{“}n\text{”})$$

are expected to be $(\alpha/2\pi)k$, where, if the $\mu-e$ conversion process were first-order in the Fermi coupling constant, k would be a number with order of magnitude unity. The experimental upper limits on these ratios are about

10^{-6} and 10^{-5} at present.[1,2] Although the exact value expected for k depends, of course, on the electromagnetic properties of the structure responsible for the $\mu-e$ conversion, a rather special model is required to make $k\approx 0$ in the two processes considered.[3] Even if such an "accident" was obtained in these reactions, one would be concerned as to why other processes like $\mu\rightarrow e+2\gamma$ or $\mu\rightarrow 3e$ are not observed. It seems more reasonable to assume[4] that μ and e are two different kinds of particles, distinguished by some kind of selection rule, and that associated with them are two different kinds of neutrinos, ν' and ν, respectively. Then in β decay, $n\rightarrow p+e+\bar{\nu}$, whereas in π decay, $\pi\rightarrow\mu+\nu'$. These two different neutrinos will be assumed throughout this paper.

B. Selection Rule Between Muons and Electrons

The selection rule between muons and electrons might be one absolutely conserving $N(\mu)$, the number of μ^- less the number of μ^+, or $N(e)$, the number of e^- less the number of e^+. In any reaction, by the conservation of leptons, $N(\mu)+N(e)=\text{constant}$, so that conservation of $N(\mu)$, conservation of $N(e)$, or conservation of $N\equiv N(\mu)-N(e)$ are all equivalent. Such an absolute or additive conservation law follows from invariance under a continuous gauge group.

The symmetry between muons and electrons might also be that of a discrete group, in which case the selection rule is one by which N is conserved modulo some integer n (multiplicative conservation law). In this case the conversion of m muons or μ neutrinos ν' into m electrons or electron neutrinos ν would be forbidden for $m<n$, but allowed for $m=n$, or a multiple thereof. For example, it is conceivable that the reactions (2.1) to (2.3) and

$$e^-+e^-\rightarrow\mu^-+\mu^- \tag{2.4}$$

or

$$\mu^++e^-\ (\text{muonium})\rightarrow\mu^-+e^+\ (\text{antimuonium}) \tag{2.5}$$

be forbidden, but that

$$e^-+e^-\rightarrow 3\mu^-+e^+ \tag{2.6}$$

be allowed, If, however, the reactions we are considering all originate in a basic Fermi or weak Yukawa interaction, then this process (2.6) is of higher order in G than any of (2.1) to (2.5).[5]

We will consider as the simplest possibility for a multiplicative conservation law the possibility that N is conserved modulo 2, so that the processes (2.1) to (2.3) are forbidden but (2.4) and (2.5) are allowed.[6]

This possibility can be expressed if we assume that the four leptons μ, ν', e, ν can be formed into an even current

$$j_\mu=(\mu\nu')+(e\nu), \tag{2.7}$$

and an odd current

$$j_\mu'=(\mu\nu)+(e\nu'), \tag{2.8}$$

and that the Fermi interaction (1.1) must be even over all. The interaction

$$\mathfrak{L}_{\text{int}}=j_\mu j_\mu^\dagger+j_\mu' j_\mu'^\dagger \tag{2.9}$$

then allows $e^++e^-\rightarrow\bar{\nu}+\nu\rightarrow\mu^++\mu^-$ and $\mu^++e^-\rightarrow\bar{\nu}'+\nu\rightarrow e^++\mu^-$.

Since ν and ν' were defined to be the neutrinos associated with e and μ in β decay and μ capture, these four-fermion interactions will be generated by

$$\mathfrak{L}_{\text{int}}=J_\mu j_\mu^\dagger+J_\mu^\dagger j_\mu. \tag{2.10}$$

In the next section we extend this notion of evenness and oddness to the strange-particle currents and find a natural *raison d'être* for a simplified variant of the veton scheme of interactions. In the remainder of this section, however, we first wish to review some experimental consequences of assuming that the four-lepton interaction (2.9) is mediated by intermediary bosons, which we shall call B mesons.

C. Intermediary Bosons

We should begin by emphasizing that the symmetry properties of the particular interaction scheme we are developing follow only from the existence of two kinds of currents, even and odd, and not from any intrinsic properties of intermediary bosons, which may or may not exist as real particles and carry evenness or oddness. We will discuss in this subsection and the following section certain additional experimental consequences which follow if B mesons do exist, and might also speak pictorially of the emission and absorption of these intermediary mesons as a means of generating the current-current interactions in which we are interested.

We emphasize that intermediate vector mesons need not exist, because of an essential difference between

[1] S. Frankel, V. Hagopian, J. Halpern, and A. L. Whetstone, Phys. Rev. **118**, 589 (1960); D. Berley, J. Lee, and M. Bardon, Phys. Rev. Letters **2**, 357 (1959).

[2] R. D. Sard, K. M. Crowe, and H. Kruger, Phys. Rev. **121**, 619 (1961); M. Conversi, L. di Lella, A. Egidi, C. Rubbia, and M. Toller, Nuovo cimento **18**, 1283 (1960).

[3] S. A. Bludman and J. A. Young, *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York), p. 564; J. A. Young, Ph.D. thesis, Lawrence Radiation Laboratory Report UCRL-9563, March, 1961 (unpublished) (earlier references are there cited).

[4] K. Nishijima, Phys. Rev. **108**, 907 (1957); J. Schwinger, Ann. Phys. **2**, 407 (1957); S. Bludman, *Gatlinburg Conference on Weak Interactions 1958* [Bull. Am. Phys. Soc. **2**, 80 (1959)]; B. Pontecorvo, Zhur. Eksptl. i Teoret. Fiz. **37**, 1751 (1959) [translation: Soviet Phys.—JETP **10**, 1236 (1960)].

[5] B. Pontecorvo, Zhur. Eksptl. i Teoret. Fiz. **33**, 549 (1957) [translation: Soviet Phys.—JETP **6**, 429 (1958)]. G. Feinberg and S. Weinberg, Phys. Rev. Letters **6**, 381 (1961), have considered the possibility of muonium-antimuonium conversion in *first* order through the four-fermion interaction $G(e\mu)(e\mu)$ or $G(ee)(\mu\mu)$. It should be emphasized that, although this interaction is first order, it is not of the charge-exchange form present in all other leptonic processes.

[6] K. Nishijima (reference 4); N. Cabibbo and R. Gatto, Phys. Rev. Letters **5**, 114 (1960); G. Feinberg and S. Weinberg, Phys. Rev. Letters **6**, 381 (1961).

symmetries under continuous and under discrete groups. In case of symmetry under a continuous group it is in the spirit of local-field theory to consider[7] the possibility that the gauge transformations generating the (additive) conservation law can be effected independently at different space-time points; when this is done, the local or extended symmetry principle demands the existence of massless vector particles connecting different space-time points. The number N of such vector mesons equals the number of infinitesimal generators in the continuous group considered. There exist simple, compact Lie groups with $N=1, 3, 8\cdots$, but not with $N=2$ or 4, infinitesimal generators. Thus, four vector mesons, which are apparently necessary in order to obtain the $\Delta I=\frac{1}{2}$ rule, cannot be irreducibly introduced in this way.

Symmetry under a discrete group, on the other hand, does not call for such localization nor compel the existence of particles maintaining the gauge principle. If intermediary particles do happen to exist, they can be massive (as any intermediary in the weak interactions must be) and of any number N corresponding to the dimension of the finite group considered.[8]

There is at present no real evidence for or against the existence of B mesons. The absence of $\mu \to e+\gamma$ is, if two different neutrinos exist, no argument against an intermediary meson. In μ decay the effect of an intermediary meson of mass M_B is[9] to increase the ρ value from that predicted by the local $V-A$ theory to

$$\rho=\tfrac{3}{4}+\tfrac{1}{3}(m_\mu/M_B)^2, \tag{2.11}$$

and to increase the μ-decay rate from that predicted in the local universal Fermi interaction theory by the relative amount

$$\Delta(\tau_\mu^{-1})/(\tau_\mu^{-1})=\tfrac{3}{5}(m_\mu/M_B)^2. \tag{2.12}$$

The existence of a boson of mass $M_B \approx 4m_\mu$ or $5m_\mu$ is therefore consistent with the present ρ-value measurements,[10] and tends to remove the 4% discrepancy between the calculated and observed μ lifetime which apparently results[11] if one takes seriously the existing measurements and radiative corrections.

D. B-Meson Decay into Leptons

The existence of real B mesons would facilitate a test for the identity of the neutrinos ν and ν'. In a high-energy neutrino experiment, the neutrinos originating from π^+ decay are supposed to allow inverse μ capture

$$\nu'+n \to \mu^- + p, \tag{2.13}$$

while allowing or forbidding

$$\nu'+n \to e^- + p, \tag{2.14}$$

according to whether $\nu' \equiv \nu$ or not. Now if B mesons exist, the semiweak processes

$$\nu' \to \mu^- + B^+, \tag{2.15}$$

and

$$\nu' \to e^- + B^+ \tag{2.16}$$

would have cross sections greater by several orders of magnitude than the reactions (2.13) and (2.14) in which we are interested. The B mesons will promptly decay into about equal numbers of μ and e secondaries of charge opposite to the primarily produced leptons, and of lesser energy. Although the decays (2.15) and (2.16) might conceal the originally proposed reaction (2.14), the presence or absence of the decay (2.16) would allow an easier test for the identity of ν and ν', provided only one B meson exists.

Now let us suppose that two different pairs of charged vector mesons, $B^\pm$ and $B'^\pm$, coupled to j_μ and j_μ' respectively, exist. Then, as Feinberg and Weinberg[6] have observed, (2.16) is forbidden, but

$$\nu' \to e^- + B'^+ \tag{2.17}$$

is allowed. Since the visible products of purely leptonic B^+ and B'^+ decay,

$$B^+ \to \mu^+ + \nu' \quad \text{or} \quad e^+ + \nu, \tag{2.18}$$

$$B'^+ \to e^+ + \nu' \quad \text{or} \quad \mu^+ + \nu, \tag{2.19}$$

are the same, the conversion of ν' into e^- will occur if there are two different kinds of bosons together with two different neutrinos, in apparently the same way as if there were only one kind of neutrino and one kind of boson.

In Sec. III(D) we will find that the decay into K mesons identifies the meson in reaction (2.17) as being

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[7] C. N. Yang and R. L. Mills, Phys. Rev. **96**, 191 (1954); S. A. Bludman, Phys. Rev. **100**, 372 (1955); R. Utiyama, Phys. Rev. **101**, 1597 (1956).

[8] In an earlier paper, Nuovo cimento **9**, 433 (1958), we assumed invariance of the weak interactions under a continuous group of dimension $N=3$, and a triple of vector mesons occurred in a natural way. As mentioned, *four* vector mesons cannot be introduced through such a local symmetry principle. Nevertheless, we should summarize here those conclusions of the earlier point of view that have direct physical consequences: If the interaction between the lepton doublets $L_1=(e\nu)$, $L_2=(\mu\nu')$ is charge-symmetric and of the $V-A$ form, then applying the Fierz rearrangement theorem, we have

$$\sum_{i,j=1,2} (\bar{L}_i\boldsymbol{\tau}L_i)\cdot(\bar{L}_j\boldsymbol{\tau}L_j) =2[(\nu\nu)-(\nu'\nu')][(ee)-(\mu\mu)]+[(\nu\nu)+(\nu'\nu')]^2 +[(ee)+(\mu\mu)]^2+4(e\mu)(\nu'\nu')+4(\mu e)(\nu\nu').$$

In a one-neutrino theory ($\nu'=\nu$), then, the weak $(\nu\nu)(ee)$ or $(\nu e)(e\nu)$ interaction vanishes identically and we have no neutrino-electron scattering $\nu+e \to \nu+e$, no $e \to e+\nu+\bar{\nu}$ "bremsstrahlung" of neutrinos in electron scattering, and no possibility of transferring stellar energy to neutrinos by the scattering process $e^-+e^+ \to \nu+\bar{\nu}$.

[9] T. D. Lee and C. N. Yang, Phys. Rev. **108**, 1611 (1957); S. A. Bludman and A. Klein, Phys. Rev. **109**, 550 (1958).

[10] The recent data, showing $\rho \gtrsim \frac{3}{4}$, are summarized in Block *et al.*, *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York), p. 551.

[11] R. K. Bardin, C. A. Barnes, W. A. Fowler, and P. A. Seeger, Phys. Rev. Letters **5**, 323 (1960); D. L. Hendrie and J. B. Gerhart, Phys. Rev. **121**, 846 (1961).

a B' rather than a B. This decay will furnish, after all, a semiweak process distinguishing the two-neutrino, two-boson theory from the one-neutrino ($\nu=\nu'$), one-boson ($B=B'$) theory, because the mesonic decay of B and B' will probably be about as frequent as their leptonic decay.

III. STRANGE-PARTICLE CURRENTS

The even and odd lepton currents [(2.7) and (2.8)] were introduced in order to forbid single $\mu-e$ conversion but to allow the $2e\rightarrow 2\mu$ processes (2.4) and (2.5). In the model (which might or might not be realistic), in which the Fermi interactions are mediated by vector mesons, these even and odd currents are coupled to even and odd mesons, B and B'. For β decay and μ capture, and all other couplings to the strangeness-preserving current J_μ, we had the interaction (2.10). This coupling of J_μ to j_μ and not to j_μ' merely expressed the convention that the neutrinos involved in β decay and μ capture (or π decay) are ν and ν' respectively.

We will now consider the question of coupling the leptons to the strangeness-changing current of strongly interacting particles S_μ. We will assume that the strangeness-preserving and strangeness-changing currents, J_μ and S_μ, like j_μ and j_μ' differ by being coupled to different mesons B and B', and that whereas J_μ was an even current (by convention), S_μ (which we will hereafter denote by J_μ') is an odd current. This extension of the evenness-oddness character from the lepton current to the current of strongly interacting particles thus expresses the existence of two kinds of noninteracting currents for strongly interacting particles, strangeness-preserving and strangeness-changing.

The interactions responsible for strange-particle leptonic and nonleptonic decays are then

$$\mathcal{L}_{\mathrm{int}}=J_\mu' j_\mu'^{\dagger}+\mathrm{H.c.}, \tag{3.1}$$

and

$$\mathcal{L}_{\mathrm{int}}=J_\mu' J_\mu'^{\dagger}+\mathrm{H.c.}, \tag{3.2}$$

respectively. Since J_μ and J_μ', being of opposite "parity," are uncoupled, whatever symmetries are involved in strange-particle decays must be incorporated into J_μ'.

A. Production of Strange Particles by High-Energy ν'

In any two-neutrino theory, ν' produces unstrange particles in association with μ^- but not with e^-; i.e., (2.13) is allowed but (2.14) is forbidden. This result follows from the distinction between ν' and ν, whether the conservation law is additive or multiplicative. It is characteristic of the interaction (3.1), however, that the strangeness-changing current J_μ' is coupled to j_μ' rather than to j_μ. In the leptonic decay of strange particles, contrary to that of unstrange particles, ν is associated with μ, and ν' with e. The neutrino production of strange particles leads to electrons,

$$\nu'+N\rightarrow\begin{cases} e^-+N+K^+ & (3.3)\\ e^-+\Sigma^-+K^++K & (3.4)\\ e^-+N+K^++K^0 & (3.5)\\ e^-+N+K^++K, & (3.6)\end{cases}$$

where $N=(n,p)$, $K=(K^0,K^+)$. The same final states with μ^- substituted for e^- are forbidden.

B. $\Delta S=2$ Leptonic Interactions

We have included as possible first-order weak leptonic processes (3.5) and (3.6), in which the strangeness changes by two. The smallness of the $K_1^0-K_2^0$ mass difference implies[12] that the $K^0\rightarrow\bar{K}^0$ transition matrix element is of second order in the weak-coupling constant. Since $K^0\rightarrow\bar{K}^0$ through the emission and subsequent absorption of virtual lepton pairs would be a second-order process in any case, the $K_1^0-K_2^0$ mass difference does not imply that $\Delta S=2$ interactions *involving leptons* must be doubly weak.

This question of the possibility of $\Delta S=2$ leptonic processes in first order is open until we observe enough Ξ decays to know whether

$$\Xi^0\rightarrow p+\begin{pmatrix} e^-+\bar{\nu}' \\ \mu^-+\bar{\nu}\end{pmatrix},\quad\text{and}\quad \Xi^-\rightarrow n+\begin{pmatrix} e^-+\bar{\nu}' \\ \mu^-+\bar{\nu}\end{pmatrix} \tag{3.7}$$

occur at a rate which is, except for the smaller phase space allowed, comparable to $\Xi^-\rightarrow\Lambda^0+\pi^-$. If the effective coupling constant for the $\Delta S=2$ Fermi interactions is the same as that for the $\Delta S=1$ Fermi interactions, then the modes (3.7) should constitute one-twentieth of all Ξ decays. It is of course possible that even though they are comparable, the $\Delta S=2$ effective coupling strengths are different by an order of magnitude from those in $\Delta S=1$, just as the $\Delta S=1$ and $\Delta S=0$ Fermi constants differ by an order of magnitude. This question of universality will be returned to in the last section.

In the above reactions $\Delta S/\Delta Q=1$, 2 so that if $\nu'\rightarrow\mu^-$ or e^- we must have $\Delta Q=1$ for the strongly interacting particles. Starting with unstrange targets, $S=1$ or 2 in the final state requires the production of K mesons. One can obtain $S=-1$ or -2 without having to produce K mesons by starting with $\bar{\nu}'$ from π^- decay, so that $\Delta Q=-1$ for the strongly interacting particles, i.e.,

$$\bar{\nu}'+\begin{pmatrix} n\\ p\end{pmatrix}\rightarrow\begin{cases} e^++\begin{pmatrix}\Sigma^-\\ \Sigma^0,\Lambda^0\end{pmatrix} & (3.8)\\[2ex] e^++\begin{pmatrix}\Xi^-\\ \Xi^0\end{pmatrix} & (3.9)\end{cases}$$

[12] L. B. Okun' and B. M. Pontecorvo, Zhur. Eksptl. i Theoret. Fiz. **32**, 1587 (1957) [translation: Soviet Phys.—JETP **5**, 1297 (1957)].

is allowed, whereas the same reactions with μ^+ in place of e^+ are forbidden.

The schizon[13] and veton[14] schemes of interaction would predict the production of muons rather than electrons in reactions (3.3) to (3.6), and (3.8) and (3.9). The $\Delta S=2$ leptonic reactions are forbidden by the schizon interaction scheme but, with μ substituted for e, are allowed by the veton scheme.

For the small fraction of ν neutrinos originating from

$$\pi^+ \rightarrow e^+ + \nu, \tag{3.10}$$

and

$$\mu^+ \rightarrow \bar{\nu}' + e^+ + \nu, \tag{3.11}$$

the roles of μ^- and e^- in reactions (3.3) to (3.6), and (3.8) and (3.9) are reversed.

C. Nonleptonic Decay of Strange Particles

Central to the scheme of even- and odd-current couplings is the idea that the strangeness-preserving and strangeness-changing currents J_μ and J_μ' are noncombining. We must therefore obtain the strangeness-changing nonleptonic interactions by the coupling (3.2) of J_μ' to itself, perhaps through the exchange of B' mesons. In order to obtain an over-all change $\Delta S=\pm 1$ in strangeness along with $\Delta Q=\Delta S$, J_μ' must consist of parts $J_{1\mu}'$ and $J_{2\mu}'$, for which $\Delta S=1$ and $\Delta S=2$ respectively. Thus

$$J_\mu' = J_{1\mu}' + J_{2\mu}'. \tag{3.12}$$

In order to obtain an over-all $\Delta I=\frac{1}{2}$, $J_{1\mu}$ and $J_{2\mu}$ must transform as $I=\frac{1}{2}$ and $I=0$ (e.g., $J_{2\mu}'=\bar{N}\Xi=\bar{p}\Xi^0+\bar{n}\Xi^-$, $J_{1\mu}'=\bar{p}\Lambda$). Then in $J_\mu' J_\mu'^\dagger$ the cross term

$$J_{1\mu}' J_{2\mu}'^\dagger + J_{2\mu}' J_{1\mu}'^\dagger \tag{3.13}$$

produces $\Delta S=\Delta Q=\pm 1$, $\Delta I=\frac{1}{2}$, whereas

$$J_{1\mu}' J_{1\mu}'^\dagger + J_{2\mu}' J_{2\mu}'^\dagger \tag{3.14}$$

produces $\Delta S=0$, $\Delta I=0$ weak interactions which will be hidden by the strangeness-preserving strong interactions.

The presence of $J_{2\mu}'$ in the interaction (3.1) will lead to the $\Delta S=2$ leptonic processes (3.5) to (3.7), and (3.9).

The interaction scheme forced upon us by the necessity of combining odd currents, J_μ' or j_μ', with odd currents is a variation of one of d'Espagnat's veton schemes[14] in which, however, J_μ' must be coupled to the *odd* lepton current j_μ'. The practical consequence of this is, as was already observed, that when the strangeness changes, the μ neutrinos ν' can produce electrons but not muons. In the conventional veton scheme,[14] ν' produces μ^- but not e^-, for strangeness-changing as well as for strangeness-preserving reactions.

D. Mesonic Decays of B and B'

The B mesons are coupled to the $I=1$, $S=0$ current J_μ of strongly interacting particles, whereas B' is coupled to J_μ', which contains both $I=\frac{1}{2}$, $S=1$ and $I=0$, $S=2$ parts. This means that in its couplings with strongly interacting particles, B is an isovector, whereas B' is both isospinor and isoscalar.

B^+ can decay into $\pi^+ + \pi^0$ or $K^+ + \bar{K}^0$. If it decays into three pions in a spherically symmetric final state, then the $(2\pi^+ + \pi^-):(2\pi^0 + \pi^+)$ branching ratio must be 1:1. B'^+ can decay into $K^+ + \pi^0$ and $K^0 + \pi^+$ with a branching ratio 1:2. These decays and branching ratios are the same as those expected in the schizon coupling scheme. B' can, if its mass is great enough, also decay with $\Delta S=2$ into $K^+ + K^0$ and into $K^+ + K^0 + \pi^0$, $2K^+ + \pi^-$, and $2K^0 + \pi^+$. The branching ratio into these last three-body final states is 1:2:2.

On the basis of phase-space estimates, these mesonic decay modes for B and B' should be comparable in frequency with the leptonic decay modes discussed in Sec. II(D). Now, in the present scheme, B' is distinguished from B by being produced in association with electrons rather than muons. Therefore, the strange-particle signatures, if energetically possible, will identify the meson in (2.17) as being a B'. This, unlike the leptonic decays (2.18) and (2.19), is an experiment of semiweak cross section, distinguishing between the predictions of a two-boson–two-neutrino and of a one-boson–one-neutrino theory.

IV. CONCLUDING DISCUSSION

A. Comparison with Other Coupling Schemes

The assumption in this paper has been that in the current-current interaction (1.1) the lepton and strongly interacting particle currents both consist of two noncombining parts, $j_\mu + j_\mu'$ and $J_\mu + J_\mu'$, so that

$$\mathcal{L}_{\text{int}} = G(j_\mu + J_\mu)^\dagger (j_\mu + J_\mu) + G(j_\mu' + J_\mu')^\dagger (j_\mu' + J_\mu'). \tag{4.1}$$

We introduced the $j_\mu' j_\mu'$ interaction while excluding $j_\mu j_\mu'$ in order to allow the $2\mu \rightarrow 2e$ processes (2.4) and (2.5) while forbidding $\mu \rightarrow e$ for (2.1) to (2.3). Applying this same splitting to the current of strongly interacting particles, we were compelled to a veton-like interaction scheme in which the strangeness-changing decays arise from the interaction of a strangeness-changing current J_μ' with itself. In a schizon-like coupling scheme the strange decays arise, on the contrary, from the coupling of J_μ' to the strangeness-preserving current J_μ. Because J_μ' and J_μ transform as $I=\frac{1}{2}$ and $I=1$ respectively, their composition to give an over-all $\Delta I=\frac{1}{2}$ then requires the coupling of neutral currents.

The present theory agrees with the conventional veton scheme but differs from the schizon scheme by (a) requiring no neutral currents; (b) requiring that intermediary mesons, if they exist, consist of two charged pairs rather than a pair of charged and a pair of neutral vector mesons; and (c) allowing $\Delta S=2$ leptonic decays (at least in the simple theory presented here).

The present theory differs from the d'Espagnat theory by (a) giving a reason, beyond that of the $\Delta I=\frac{1}{2}$ rule we are trying to explain, why J_μ and J_μ' should not interact, and (b) asserting that μ neutrinos ν' can

[13] T. D. Lee and C. N. Yang, Phys. Rev. **119**, 1410 (1960).
[14] B. d'Espagnat, Nuovo cimento **18**, 287 (1960).

produce electrons, and in fact must transmute into electrons (and not muons) in those leptonic-decay or production processes in which the strangeness changes.

The experimental tests among the present theory and the schizon and veton theories can be summarized as follows.

(A) If intermediary mesons exist:

(1) In all three theories, B can be produced from π-decay neutrinos ν' in association with μ. Our theory is distinguished from the other two theories, however, by allowing (2.17), B' production in association with e.

(2) In all three theories the B, B' decays (2.18) and (2.19) into μ or e and some kind of neutrino are allowed. In the nonleptonic B decays, those involving $\Delta S=0$ and $\Delta S=1$ lead to final states of $I=1$ and $I=\frac{1}{2}$ respectively. In our theory and in the conventional veton theory, but not in the schizon theory, $\Delta S=2$ B' decays into two K mesons, leading to $I=0$ final states, are possible if the B'-meson mass exceeds $2M_K$.

(B) Whether or not intermediary mesons exist:

(1) In our theory and in one of d'Espagnat's veton schemes $\Delta S=2$ leptonic interactions are allowed; such processes are not admitted in the schizon coupling scheme.

(2) In all three theories, high-energy ν' produce μ^- but not e^- in strangeness-preserving reactions. The theory presented here is distinguished from the conventional veton and schizon theories by predicting that in strangeness-changing neutrino production experiments (3.3) to (3.6), and (3.8) and (3.9), e^- rather than μ^- will be produced.

(C) If there is only one neutrino ($\nu\equiv\nu'$), muons and electrons can in all cases be produced indiscriminately. In any case the weak process (2.14) tells whether or not the muon and electron neutrinos are the same. If intermediary bosons exist, however, the sequence (2.17) followed by $B'\rightarrow 2K$ or $2K+\pi$ (but not $\rightarrow 2\pi$ or $K+\bar{K}$) is an experiment of semiweak cross section that discriminates a two-boson ($B\neq B'$), two-neutrino ($\nu\neq\nu'$) situation from that in which there exist only one neutrino and one charged boson.

B. Discussion

The schizon scheme is symmetric in its treatment of the currents J_μ and J_μ', but gives no explanation for the failure of universality by which those neutral couplings introduced for the currents of strongly interacting particles are absent for the lepton currents. This argument, unless B^0 and $\bar{B}^0$ mesons can be detected, involves "explaining" the $\Delta I=\frac{1}{2}$ rule by a construction contradicting universality. The veton schemes, on the other hand, avoid the introduction of neutral currents by assuming that different baryon currents are differently coupled (through what d'Espagnat calls $w^\pm$ and $v^\pm$ mesons), whereas the lepton current (2.7) is coupled through both $w^\pm$ and $v^\pm$. d'Espagnat's formulation offers, however, a variety of possibilities without any apparent reason for the particular kind of dissymmetry in the baryon and lepton couplings by which J_μ' couples to J_μ' and not to J_μ.

In this paper we have distinguished even and odd weak-interaction currents, being careful *not* to assign such quantum numbers to the strongly interacting particles themselves. We have, in a sense, done no more than argue for the division of the current-current interaction (1.1) into the form (4.1). From the absence of processes in which muons and electrons interconvert singly, we have arrived at the necessity for the two currents J_μ and J_μ' of different strangeness, and for the $J_\mu'J_\mu'$ way of getting the strange-particle decays. We have been compelled towards a variant of one of d'Espagnat's veton schemes, free of neutral currents, permitting (but not requiring) the $\Delta I=\frac{1}{2}$ rule, in which, however, leptons and baryons are treated rather symmetrically, and for which muon neutrinos are associated with electrons in strangeness-changing processes.

C. Question of Universality

The phrase "universal coupling scheme" is used to denote a scheme in which processes that are somehow comparable and involve different particles proceed with comparable coupling strength. The Fermi interactions have, of course, never been universal in the sense that there were *no* restrictions on the four fermions assumed to interact with the same coupling constant. Recent experimental data[15] have emphasized that the Fermi interaction is not universal if the baryons assumed to participate are naively taken to be those physical particles apparently involved in the strong interactions at low energies. In fact, an argument has been given[16] that the permitted interactions help to define the particles.

The question as to which combinations of particles enter into the Fermi currents $\mathcal{J}_\mu$ is thus bound up with the relation of weak- and strong-interaction phenomena. It is for this reason that we have avoided any statement about the rates at which processes allowed by the selection rules (like Λ or Ξ β decay) actually proceed. In fact, because Λ β decay proceeds at a rate comparable with but still of an order of magnitude less than neutron decay, one should be cautious in predicting exactly the rate at which the $\Delta S=2$ leptonic processes like (3.7) must take place.

In the interaction (4.1), β decay and μ capture proceed through only the first term, while μ^- decay (leading to $\nu'+e^-+\bar{\nu}$ and $\nu+e^-+\bar{\nu}$) proceeds through both terms on the right-hand side. This means that, if the lepton currents are normalized by (2.7) and (2.8), the equality of ft values in μ and β decay requires that, for the latter,

$$J_\mu=\sqrt{2}\bar{p}n.$$

We cannot say how reasonable or unreasonable an expression of universality is involved in this $\sqrt{2}$.

[15] W. E. Humphrey, J. Kirz, A. H. Rosenfeld, J. Leitner, and Y. I. Rhee (to be published).

[16] S. A. Bludman, Nuovo cimento 9, 433 (1958).