Theory of Neutral Leptonic Currents

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d'Espagnat's theory of weak interactions is extended to include neutral leptonic currents. It is found possible to obtain agreement with the experimental absence of neutral lepton currents in all processes involving hadrons in a natural way, but only by introducing $i\equiv\sqrt{(-1)}$ multiplying the entire leptonic Lagrangian. It is also found natural to couple the μ leptons and the e leptons in symmetrical, but different, ways. The consequences of the coupling scheme, in addition to the sought-for absence of most neutral currents, are: (1) separate conservation of μ and e leptons, (2) a mechanism for the $\mu-e$ mass difference, (3) production of μ pairs in e-type neutrino scattering and in μ scattering. If, in addition, the decoupling of hadronic and leptonic neutral currents which we have set up is broken by any small perturbation, CP violation results. The experimental consequences of two such possible symmetry-breaking mechanisms are discussed.

I. INTRODUCTION

In the current-current formulation of the weak interactions, the presence of both charged and neutral hadronic currents, but only charged leptonic currents, is a puzzle. All theories of intermediate vector bosons (W for example) which successfully explain the $\Delta I=\frac{1}{2}$ rule, have been forced to introduce neutral as well as charged W's,[1] and then to postulate *ad hoc* that the neutral W's are not coupled to leptons. This is an unsatisfactory situation for W theories. We shall attempt here to introduce W couplings to leptons in a reasonably natural and universal way, and see if some sort of cancellation of many of the neutral leptonic currents can be arranged.

We choose as our starting point d'Espagnat's theory, which incorporates a U_3 triplet of W's.[2] There are two reasons for this choice: First, this theory offers the simplest explanation of the octet enhancement, i.e., the fact that the hadronic current-current terms $J^\dagger J$ that are actually coupled in nonleptonic decays seem to belong only to an octet, whereas J itself belongs to an octet. (A similar theory has been proposed by Ryan, Okubo, and Marshak.[3]) Second, besides the charged W, there are *two* neutral bosons, W^2 and W^3, in d'Espagnat's scheme, so there is some possibility of cancellation of the type we seek.

To d'Espagnat's hadronic weak interaction we add the leptons in a new "universal" fashion with the following consequences:

(1) The separate conservation of μ and e leptons. (Section II.)

(2) Absence of weak neutral leptonic currents (other than those resulting from the usual effects of electromagnetism) in all processes involving hadrons. (Section III.)

(3) Some definite, but difficult to observe, differences for the weak interactions of μ and e leptons in leptonic processes not directly involving hadrons. (Section IV.)

(4) A neutral W self-energy loop for the μ, but not for the e. (Section IV.)

The theory, at the stage described, conserves CP to all orders of perturbation, despite the presence of an imaginary coupling constant for the weak leptonic Lagrangian. (Section V.)

If, however, we upset our decoupling of neutral leptonic currents from hadrons by some additional CP-conserving interaction of W's, then we predict the emission of CP-odd neutral leptonic currents (specifically $\bar{\mu}\mu$ and $\bar{\nu}_e\nu_e$). The interference of these with the usual (CP-even) neutral lepton pairs $\bar{\mu}\mu$ induced by electromagnetism causes a small CP violation. This may be the mechanism of the $K_2^0\to\pi^+\pi^-$ amplitude observed by Christenson, Cronin, Fitch, and Turlay.[4] A possible form for such an additional interaction for W's might be such as to cause the W's to feel the effect of the SU_3-violating medium-strong interactions, thus inducing a W_2-W_3 mass difference. We show in Sec. IV that this would cause CP viloation in our scheme, accompanied by observable emission of $\mu^+\mu^-$ pairs in K decay.

Similarly, an electromagnetic interaction of W's via an intrinsic magnetic moment of neutral W's would serve to produce emission of CP-odd neutral leptonic pairs, and thus CP violation. This is explored in Sec. VII.

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[1] See, however, B. d'Espagnat, in *Proceedings of the Tenth International Conference on High-Energy Physics at Rochester, 1960*, edited by E. C. G. Sudarshan, J. Tincot, and A. C. Melissions (Interscience Publishers, Inc., New York, 1961), p. 589.

[2] B. d'Espagnat, Phys. Letters **7**, 209 (1963). See also, B. d'Espagnat and Y. Villachon, Nuovo Cimento **33**, 948 (1964) and B. d'Espagnat, CERN Report No. 64-42, 1964 (unpublished).

[3] C. Ryan, S. Okubo, and R. E. Marshak, Nuovo Cimento **34**, 753 (1964).

[4] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters **13**, 138 (1964). For a recent review of this subject see J. S. Bell and J. Steinberger, in *Proceedings of the Oxford International Conference on Elementary Particles, 1965* (Rutherford High Energy Laboratory, Harwell, England, 1966), pp. 193–222 and C. N. Yang, in *Proceedings of the Argonne International Conference on Weak Interactions, 1965*, Argonne National Laboratory Report No. ANL-7130, 1965 (unpublished), p. 29.

II. FORMULATION

The d'Espagnat hadronic Lagrangian is

$$^{H}\mathfrak{L}=\cos\theta(J^2{}_1W^1+J^2{}_2W^2+J^2{}_3W^3)+\sin\theta(J^3{}_1W^1+J^3{}_2W^2+J^3{}_3W^3)+\text{Hermitian conjugate}, \quad (1)$$

with

$$(J^i{}_jW^j)^*=W_jJ^j{}_i, \quad i,j=1,2,3.$$

The $J^i{}_j$ are the usual octet or nonet of hadronic currents, and the W^j are a unitary triplet (see Fig. 1). The universal coupling constant

$$g^2=(G/\sqrt{2})M_W{}^2=(1.02/\sqrt{2})\times10^{-5}(M_W{}^2/M_p{}^2)=0.72\times10^{-5}\lambda^2 \quad (2)$$

and the space-time variables of the currents (sum of a vector and an axial-vector part) are suppressed for convenience. This Lagrangian is not a scalar under U_3 but rather a linear combination of the neutral components "2" (first line) and "3" (second line) of a U_3 triplet. Notice that the strangeness-changing currents, $J^2{}_3$, $J^3{}_2$, $J^1{}_3$, and $J^3{}_1$, are distributed in a curious fashion with respect to the coefficients which are the sine and cosine of the Cabibbo[5] angle θ. Under rotations about the second axis in U space, the "2" and "3" components of $^{H}\mathfrak{L}$ transform like the neutral doublet of a triplet. Thus in a frame (primed frame) obtained from the usual one by such a rotation through an angle 2θ, the Lagrangian $^{H}\mathfrak{L}$ assumes the very simple form

$$^{H}\mathfrak{L}=J'^2{}_iW'^i+\text{H.c.} \quad (3)$$

The repeated index involves a summation i running from 1 to 3.

Let us now try to couple the W's to the leptonic currents. These currents are of the form

$$l^Al_B=j^\alpha(\bar{A},B)=\bar{\psi}_Ai\gamma^\alpha(1+i\gamma_5)\psi_B,$$

which correspond to right chirality for the particles A, B (created by ψ_A,ψ_B) and left chirality for their antiparticles $\bar{A}$, $\bar{B}$; so our shorthand notation l^Al_B for the leptonic current implies, respectively, left (right) chirality for the particles created by the field whose symbol appears on the left (right) of the expression for the leptonic current.

We assign indices 1, 2 to the leptons. For instance, for the e leptons we denote by l^1, l^2 the fields creating, respectively, the e^- and ν_e. Then $l_1=(l^1)^*$, $l_2=(l^2)^*$ create e^+ and $\bar{\nu}_e$. [See Fig. 2(a).] We know we must have (for β decay for instance) the coupling $l^2l_1W^1+\text{H.c.}$, where the field W^1 creates a charged W^- intermediate boson. By analogy with Eq. (3), it is natural to write the interaction of e leptons with W's in the following way:

$$^{e}\mathfrak{L}=l^2l_1W'^1+l^2l_2W'^2+\text{H.c.}, \quad (4a)$$

where the second term couples the neutral current $\nu_e\bar{\nu}_e$ to the neutral W'^2.

[5] N. Cabibbo, Phys. Rev. Letters **10**, 513 (1963).

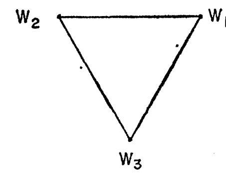


FIG. 1. The unitary triplet of W's.

Although for the e leptons, the 1, 2 indices have been attributed to e^- and ν_e in analogy with the charged W^1 and neutral W'^2, it would have been possible to make the opposite choice, thus creating a "charge-displaced" doublet. We illustrate this for the μ leptons with the assignment that L_1, L_2, L^1, L^2 create, respectively, ν_μ, μ^-, $\bar{\nu}_\mu$, μ^+. [See Fig. 2(b).] The Lagrangian similar to (4a) which keeps the known chiralities is then

$$^{\mu}\mathfrak{L}=W'^1L_1L^2+W'^2L_2L^2+\text{H.c.} \quad (4b)$$

Its first term contains the interaction necessary to μ capture and μ decay, i.e., $W^-\nu_\mu\mu^+$, while the second term couples the neutral current $\mu^-\mu^+$ to the neutral W'^2.

These two coupling schemes for leptons yield the same coupling for the charged currents but differ for neutral currents. We find the possibility of coupling μ and e leptons differently, but in a manner symmetrical enough to ensure the observed μ-e symmetry, an attractive feature; we know, after all, that the μ and e are not the same. So we keep the coupling the way we have written it. (Obviously a mirror scheme is obtained by exchanging the μ-lepton and e-lepton attribution. We return to this point later in Secs. IV and IX.)

Hence our weak-interaction Lagrangian is

$$\mathfrak{L}_W=J'^2{}_iW'^i+\epsilon(l^2l_k+L_kL^2)W'^k+\text{H.c.}, \quad (5)$$

where $i=1, 2, 3$; $k=1, 2$; and ϵ is an adjustable constant. It is the $2'$ component of a doublet under the SU_2 group, acting on the $1'$, $2'$ indices.

As a pleasant result of our charge displacement of lepton doublets, we note that all terms of the form $L^2l_kW'^k$ or $l_2L^kW'_k$ must be rejected, since they do not conserve the electric charge. As a consequence, our Lagrangian contains a desirable feature, *the separate conservation of μ leptons and e leptons*.

The question must be asked whether the leptonic Lagrangian chosen is sufficiently universal; W'_3 is not coupled, which seems strange. However, this coupling is as universal as is consistent with the apparent doublet structure of the leptons, contrasted to the SU_3 structure of the hadrons. With three W's and two leptons, one linear combination of W's must be left

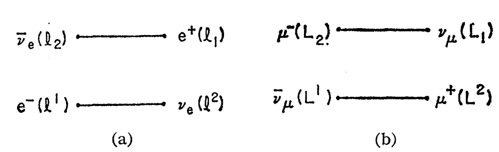


FIG. 2. (a) Doublet assignments to e leptons. (b) Doublet assignments to μ leptons.

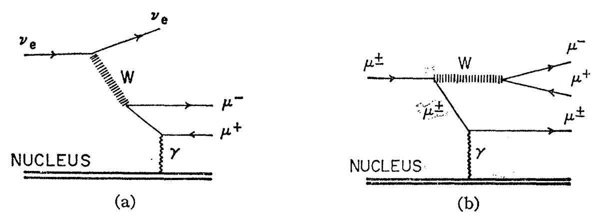


FIG. 3. (a) μ-pair production in ν_e scattering. (b) μ-pair production in $\mu^\pm$ scattering.

out. By rotation one can then go to a frame in which one W is not coupled at all. We have chosen this to happen in that frame in which ${}^H\mathfrak{L}$ is simplest. (One might compare the situation with the electromagnetic coupling, in which the charge e is a universal constant, yet not all particles are charged.)

The U_3 group which acts on hadrons and W's cannot act, except trivially, on leptons, which are two-component objects. Therefore we must treat the leptons as scalars under SU_3 rotations.[6]

We now go to the physical frame, by the Cabibbo rotation:

$$W'=W'^1,\quad W'^2=W^2\cos\theta+W^3\sin\theta.$$

Then

$$\begin{aligned}\mathfrak{L}_W=&[J^2{}_1W^1+J^2{}_2W^2+J^2{}_3W^3+\epsilon(\nu_e\bar{\nu}_e+\mu^-\mu^+)W^2]\cos\theta\\&+[J^3{}_1W^1+J^3{}_2W^2+J^3{}_3W^3+\epsilon(\nu_e\bar{\nu}_e+\mu^-\mu^+)W^3]\sin\theta\\&+\epsilon(\nu_e e^+ +\nu_\mu\mu^+)W^1+\text{H.c.}\quad(6)\end{aligned}$$

As a consequence of the separate conservation of μ and e leptons, μ decay and β decay proceed only via W^1. The usual condition of observed universality therefore requires $|\epsilon|=1$.

III. NEUTRAL SEMILEPTONIC PROCESSES

We now investigate neutral hadron lepton transitions, starting first with strangeness-changing ones:

$${}^H\mathfrak{L}(\Delta S=1,\Delta Q=0)=J^3{}_2(W^2\sin\theta+W_3\cos\theta),\quad(7)$$

where the second term comes from the H.c. part of Eq. (1). If we now contract this with the leptonic Lagrangian, we find

$$\begin{aligned}\mathfrak{L}_W(\Delta S=1,\Delta Q=0)=&J^3{}_2(W_3W^3\epsilon+W^2W_2\epsilon^*)\\&\times(\sin\theta\cos\theta)(\nu_e\bar{\nu}_e+\mu^-\mu^+).\quad(8)\end{aligned}$$

Since only a single hadronic current is involved and the relevant leptonic current is self-conjugate, a cancellation is possible. Under the assumption that W^2 and W^3 have the same mass, we achieve cancellation of the strangeness-changing neutral currents by choosing $\epsilon^*=-\epsilon$ or

$$\epsilon=i.$$

This is a suitably simple value for the adjustable parameter, which formally opens the door for a CP violation into the theory. However, the weak interaction given by $\mathfrak{L}_W$ in Eq. (6) with $\epsilon=i$ does not contain any CP violation. (We discuss this point in Sec. V.)

We now examine the non-strangeness-changing neutral semileptonic processes. Since all *decays* of this class are allowed also by electromagnetism, for all practical purposes this class of phenomena consists of neutrino-scattering experiments (and of weak corrections to Coulomb scattering of charged leptons). We find two contributions, one for the $J^2{}_2$ current, the other for $J^3{}_3$. The $J^2{}_2$ contribution comes from two H.c. terms,

$$\begin{aligned}[(\cos\theta)J^2{}_2W^2W_2(-i)\cos\theta+(\cos\theta)J^2{}_2W_2W^2i\cos\theta]\\\times(\nu_e\bar{\nu}_e+\mu^-\mu^+),\quad(9)\end{aligned}$$

whose sum is zero. The same type of cancellation happens for the $J^3{}_3\sin^2\theta$ terms. Therefore the $\Delta S=0=\Delta Q$ currents cancel also.

At first sight this seems like throwing out the baby with the bath water. It is not. First, we *do* have neutral currents, for purely leptonic processes; we study these in the next section. Second, any deviation from exact cancellation in the semileptonic processes discussed above will produce $\mu^-\mu^+$ and $\nu_e\bar{\nu}_e$ pairs from hadrons (see Secs. VI–VIII).

IV. LEPTONIC PROCESSES

(1) As shown at the end of Sec. II, the decay $\mu^+\rightarrow e^++\nu_e+\bar{\nu}_\mu$ proceeds in the usual way, neutral currents being excluded.

(2) The reaction process $\mu^++\mu^-\rightarrow\nu_e+\bar{\nu}_e$ is obviously predicted by $\mathfrak{L}_W$. This is hard to observe; neutrinos from $\mu^++\mu^-\rightarrow\nu_\mu+\bar{\nu}_\mu$ are expected in any case from charged W exchange.

(3) μ-pair production by ν_e scattering and μ scattering: The virtual processes $\nu_e\rightarrow\nu_e+\mu^++\mu^-$ and $\mu^\pm\rightarrow\mu^\pm+\mu^++\mu^-$, proceeding via an intermediate neutral W, are predicted by the Lagrangian given in Eq. (6). These processes can be made real by photon exchange with a nucleus, as shown in Figs. 3(a) and 3(b), respectively.[7] There are four other similar processes of this 4-lepton kind, allowed by conventional weak-interaction theories, and corresponding to the four permutations of the two terms in the charged lepton currents. One of them ($\nu_\mu\rightarrow\mu^+\mu^-\nu_\mu$) results in μ pairs. These conventional processes have been calculated by

[6] The SU_2 group considered after Eq. (5) (let us call it G in this footnote) is therefore not a subgroup of the group SU_3 of invariance for strong interactions. For the technically interested reader, here is the relation between these two groups: Let H be the SU_2 subgroup of SU_3 acting on the 1′, 2′ components of the basic triplet, and L be the SU_2 subgroup acting on leptons. Then G is the diagonal subgroup of the direct product $H\times L$.

[7] The process $\mu^\pm+\text{nucleus}\rightarrow\mu^\pm+\mu^++\mu^-+\text{nucleus}$ was pointed out to us by Dr. E. Picasso. Of course, this process would be in competition with the corresponding one in which the W is replaced by a photon. However, for a *real* W, the competition is not necessarily unfavorable.

Czyż, Sheppey, and Walecka.[8] They are down by a factor $\sim 10^{-5}$ compared to the "elastic" process $\nu_\mu + n \rightarrow \mu^- + p$ at present neutrino-beam energies ($\sim$1 BeV), and by a factor $\sim 10^{-3}$ at 10 BeV.

In principle, observation of μ pairs as a function of the ν_e/ν_μ ratio in the beam could test the existence of our neutral current, but the experiment looks impossibly difficult with present accelerators.

(4) The processes (partly virtual)

$$\mu^\pm \rightarrow \mu^\pm + W^0 \rightarrow \mu^\pm, \quad (10a)$$

and

$$e^\pm \rightarrow e^\pm + W^0 \rightarrow e^\pm. \quad (10b)$$

With our interaction, (10a) is fully allowed; (10b) is strictly forbidden. Hence the μ has a self-energy loop (see Fig. 4) that the electron does not have. Perhaps this is why it is heavier. Such self-energy loops are not well understood. The only remark we want to make here is that although the coupling constant g is not large, the self-energy integrals are much less damped by the form factors of the vertices than in the strong interaction. We expect the spatial structure of leptons to be much less extended than that of hadrons. In any case, the old puzzle, that the μ and e were identical in their coupling but had different masses, is here somewhat changed. The problem is now to explain the mass difference as a direct, or indirect, consequence of the assumed difference in coupling to neutral W's. This assumption is also supported by its consequence of separate conservation of μ and e leptons.

It is true that the sign of the contribution of (10a) to the μ self-energy is not known (except in the lowest order perturbation theory). If it were negative, we would have to permute the role of e and μ leptons. This gives analogous consequences to (2) and (3), even slightly easier to detect:

(2′) $e^+ + e^- \rightarrow W^0 \rightarrow e^+ + e^-$ will give resonance scattering of electrons at BeV energies in the center-of-mass system that can be reached by colliding beams.

(3′) The processes corresponding to those of Figs. 3(a) and 3(b) are now

$$\nu_\mu + \text{nucleus} \rightarrow \nu_\mu + e^+ + e^- + \text{nucleus},$$

and

$$e^+ + \text{nucleus} \rightarrow e^\pm + e^+ + e^- + \text{nucleus}.$$

They are not more difficult to detect than the four other similar processes predicted in conventional theories and as yet unseen.

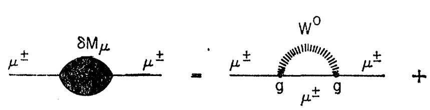


FIG. 4. Self-energy loop for the μ.

[8] W. Czyż, G. C. Sheppey, and J. D. Walecka, Nuovo Cimento 34, 404 (1964).

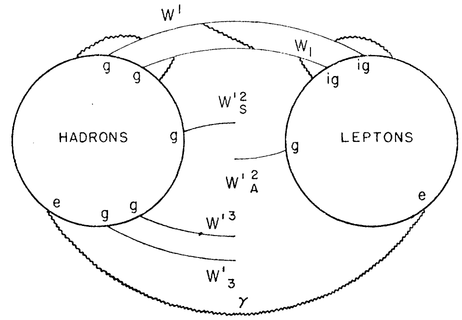


FIG. 5. Links between hadrons and leptons as given by $\mathcal{L}_0 + \mathcal{L}_{SU_3} + \mathcal{L}_W + \mathcal{L}_{em}$. The coupling constant g is given in Eq. (2). Note that only the *charged* W's (W^1 and W_1) are coupled to both hadrons and leptons. The *neutral* W's are coupled *either* to the hadrons ($W'_S{}^2 = W'^2 + W'_2$; W'_3 and W'^3) *or* to the leptons [$W'^2_A = i(W'^2 - W'_2)$]. The wavy lines correspond to "photon" links.

To summarize, we have deviated from μ-e universality, but only in the coupling to neutral W's. Something of this sort must be done, since the μ and the e are not the same. It remains to be seen whether this is the right way to do it.

V. PROPERTIES OF THE LAGRANGIAN

Let us summarize the picture of the world which we obtain. For simplicity we consider first the Lagrangian part $\mathcal{L}_0 + \mathcal{L}_{SU_3} + \mathcal{L}_W$.

The hadrons interact among themselves through $\mathcal{L}_{SU_3}$ and, as is explained in d'Espagnat's papers,[2] they are coupled to the five fields

$$W_1, W^1, W'_3, W'^3, \quad \text{and} \quad W'_S{}^2 = W'_2 + W'^2.$$

Note that since $J'^2{}_2$ is a self-charge conjugated current, its total coupling to the W's is $gJ'^2{}_2(W'^2 + W'_2)$. Thus, the sixth field

$$W'_A{}^2 = i(W'^2 - W'_2)$$

is not coupled to hadrons; but, by the choice $\epsilon = i$ in Eq. (6), we have coupled this field to leptons. The only other W fields coupled to leptons are the charged ones W^1, W_1. In Fig. 5 we draw the ideogram which represents this simplified version of the world. The two Hermitian fields

$$W'_S{}^2 = W'^2 + W'_2 \quad \text{and} \quad W'_A{}^2 = i(W'^2 - W'_2)$$

are completely uncoupled to each other. This is the origin of the cancellations exhibited in Sec. III. There we worked in the physical frame. For reference in this frame the uncoupled fields are

$$W'_{2S} = W'_S{}^2 = (W^2 + W_2)\cos\theta + (W^3 + W_3)\sin\theta,$$
$$W'_{2A} = W'_A{}^2 = i(W^2 - W_2)\cos\theta + i(W^3 - W_3)\sin\theta.$$

There are lepton-lepton processes via W^1, W_1, and $W'_A{}^2$ fields. In the previous section we studied those processes involving neutral $W'_A{}^2$; but the hadron and lepton parts of the world communicate only via charged

W's. This implies the absence of neutral leptonic currents from hadrons.

We also note that the Lagrangian $\mathcal{L}_0+\mathcal{L}_{SU_3}+\mathcal{L}_W$ preserves CP. Indeed, to observe CP violation in a transition from a state A to a state B one must have an interference between two amplitudes which correspond to two transitions going via an even and an odd number of ig coupling constants, respectively. This cannot occur, since H-H and L-L transitions all have an even number, and H-L an odd number.

Of course, our Lagrangian is not complete. We have to add the electromagnetic part $\mathcal{L}_{\text{em}}$ and the strong-coupling part $\mathcal{L}_{SS}$ that breaks SU_3.

A. Influence of $\mathcal{L}_{\text{em}}$

We consider here only the "minimal" electromagnetic interaction; that is, e.g., for the W, only with the electric charge of W^1. This interaction creates a new link between the hadron part and the lepton part of the world. For example,

$$p+\bar{p}\rightarrow\gamma\rightarrow\mu^++\mu^-.$$

This implies, as in many conventional theories, production of neutral leptonic currents from hadrons. This mechanism is CP-even.

If $\mathcal{L}_{\text{em}}$ is "minimal," it still gives electromagnetic properties to the neutral W's. The neutral W'_3 and W'^3 have an induced magnetic moment of the order $g^2(e\hbar/M_Wc)$, and also a quadrupole electric moment. The neutral W'_2 and W'^2 have none because they are coupled to the other particles only through their Hermitian part W'_{2S} (coupled to hadrons), or W'_{2A} (coupled to leptons). All the neutral bosons can decay into three or more photons. (Decay into two photons is forbidden by angular-momentum conservation.)

Since the photon link does not carry an electric charge, it does not interfere with an H-L transition or a charged boson. Also, since electromagnetic radiative corrections do not directly modify the *vertex* at which W'_2 are emitted, the hadronic current for W'_2 emission is still Hermitian, so it still only emits $W'_S{}^2$ directly. Further, if the magnetic moments of W'_2 and W'^2 are zero, there will be no radiative corrections to the $W'_S{}^2$ propagator, and so no purely electromagnetic $W'_S{}^2\rightarrow W'_A{}^2$ transition. All this means is that there are no CP-odd neutral leptonic currents for the photon link to interfere with, and hence no CP violation.

B. Influence of $\mathcal{L}_{SS}$

If this part of the Lagrangian involves only hadrons, it does not create any new links between the hadron island, the lepton island, and the W bridges of Fig. 5, because the hadronic coefficient of W'^2 is still Hermitian. So again no CP-odd neutral leptonic current from hadrons results, and no CP violation.

Another general way to see the absence of CP-odd neutral leptonic currents then giving rise to CP violation is to note that the i that was used in the coupling of neutral leptonic currents can be absorbed in the definition of the Hermitian W'_{2A} field. Then the coupling

$$g(\mu\bar{\mu}+\nu_e\bar{\nu}_e)W'_A{}^2$$

will not produce CP violation.

C. Summary

Hence we have shown that one can introduce neutral leptonic currents in such a way that they manifest themselves only in purely leptonic processes. This is completely compatible with experiments, but has new consequences which are in principle observable [see Sec. IV (3)]. Although an imaginary coupling constant ig was necessarily introduced into the leptonic part of the weak Lagrangian, we also showed that this does not necessarily imply CP violation.

However, any small defect of the exact cancellation shown in Sec. III for neutral semileptonic currents will yield a correspondingly small CP violation, and at the same time predicts observable emission of CP-odd neutral lepton pairs. This can be done by direct couplings of the W's other than those hitherto considered. In order to be able to make predictions, we adopt a phenomenological approach and study two different mechanisms to spoil the cancellation of Sec. III: (i) a W_2-W_3 mass difference, (ii) a W_2 *intrinsic* magnetic moment. The consequencies of these two mechanisms for CP violation are explored in Secs. VI and VII. Note that the two mechanisms are in *themselves* CP-conserving.

VI. EFFECTS OF A W_2-W_3 MASS DIFFERENCE

Such a mass difference breaks U_3 invariance but not isospin invariance if W_1 and W_2 have the same mass. We study phenomenologically the consequences of such a mass difference without attempting the much more difficult task of explaining its origin.

TABLE I. Branching ratios for hyperon decays involving neutral leptonic currents.

Decay mode	Induced neutral currents	β mechanism (W_2-W_3 mass difference)	α mechanism (intrinsic magnetic moment for neutral W's)
$\Lambda\rightarrow n+\nu_e+\bar{\nu}_e$	Negligible	$\sim3\beta^2 10^{-3}$	$\sim\alpha^2 10^{-3}$
$\Lambda\rightarrow n+e^++e^-$	$\sim3\times10^{-6}$	Uncoupled	Uncoupled
$\Sigma^+\rightarrow p+\nu_e+\bar{\nu}_e$	Negligible	$\sim5\beta^2 10^{-3}$	$\sim\alpha^2 10^{-3}$
$\Sigma^+\rightarrow p+e^++e^-$	$\sim4\times10^{-6}$	Uncoupled	Uncoupled
$\Sigma^+\rightarrow p+\mu^++\mu^-$	$\sim8\times10^{-8}$	$\sim0.8\beta^2 10^{-4}$	$\sim\alpha^2 10^{-5}$
$\Xi^0\rightarrow\Lambda^0+\nu_e+\nu_e$	Negligible	$\sim6\beta^2 10^{-3}$	$\sim\alpha^2 10^{-3}$
$\Xi^0\rightarrow\Lambda^0+e^++e^-$	$\sim3\times10^{-6}$	Uncoupled	Uncoupled

TABLE II. Branching ratios for K decays involving neutral leptonic currents.

Decay mode	Induced neutral leptonic currents	β mechanism (W_2-W_3 mass difference)	α mechanism (intrinsic magnetic moment for neutral W's)	Experimental limits
$K_1^0 \to e^+ + e^-$	$\sim 10^{-8}$	Uncoupled	Uncoupled	?
$K_1^0 \to \mu^+ + \mu^-$	$\sim 10^{-8}$	$7\beta^2 \times 10^{-2}$	Negligible	?
$K_2^0 \to e^+ + e^-$	$\lesssim 10^{-11}$ [a]	Uncoupled	Uncoupled	$\lesssim 10^{-4}$ [b]
$K_2^0 \to \mu^+ + \mu^-$	$\lesssim 4 \times 10^{-8}$ [a]	Negligible	$\sim \alpha^2$	$\lesssim 10^{-4}$ [b]
$K^+ \to \pi^+ + \nu_e + \bar{\nu}_e$	Negligible	$0.65\beta^2$	$\sim 5\alpha^2 10^{-2}$	?
$K^+ \to \pi^+ + e^+ + e^-$	1.0×10^{-7} [c]; $\sim 10^{-6}$ [a,d]	Uncoupled	Uncoupled	$\lesssim 1.1 \times 10^{-6}$ [e]
$K^+ \to \pi^+ + \mu^+ + \mu^-$	$\sim 0.25 \times 10^{-7}$	$0.12\beta^2$	$\sim \alpha^2 10^{-2}$	$\lesssim 3 \times 10^{-6}$ [f]
$K_1^0 \to \pi^0 + \nu_e + \nu_e$	Negligible	Negligible	Negligible	?
$K_1^0 \to \pi^0 + e^+ + e^-$	$\sim 0.8 \times 10^{-8}$ [d]	Uncoupled	Uncoupled	?
$K_1^0 \to \pi^0 + \mu^+ + \mu^-$	$\sim 10^{-9}$	Negligible	$\sim 3\alpha^2 10^{-4}$	?
$K_2^0 \to \pi^0 + \nu_e + \bar{\nu}_e$	Negligible	$2.8\beta^2$	Negligible	?
$K_2^0 \to \pi^0 + e^+ + e^-$	Negligible	Uncoupled	Uncoupled	?
$K_2^0 \to \pi^0 + \mu^+ + \mu^-$	Negligible	$0.5\beta^2$	Negligible	?

[a] See Ref. 9.
[b] See D. W. Carpenter *et al.*, Ref. 10.
[c] N. Cabibbo and E. Ferrari, Nuovo Cimento **18**, 928 (1960).
[d] M. Baker and S. L. Glashow, Nuovo Cimento **25**, 857 (1962).
[e] See U. Camerini *et al.*, Ref. 15.
[f] See Ref. 11.

Our phenomenological study depends on only one dimensionless parameter,

$$\beta = 2(M_3 - M_2)/(M_3 + M_2)\,, \tag{11}$$

where M_3 and M_2 are, respectively, the masses of the W_3 and W_2 bosons. The cancellation in Eq. (8) will be upset when $\beta \neq 0$. Indeed $(W_3W^3 - W^2W_2)$ in this equation represents the difference of the propagators

$$K_{\mu\nu}^{(3)} - K_{\mu\nu}^{(2)} = \frac{g_{\mu\nu} - k_\mu k_\nu M_3^{-2}}{k^2 - M_3^2} - \frac{g_{\mu\nu} - k_\mu k_\nu M_2^{-2}}{k^2 - M_2^2}\,.$$

When this expression is expanded in powers of β, the lowest term reads

$$(W_3W^3 - W^2W_2)_{\mu\nu} = 2\beta[M^2/(k^2 - M^2)^2] \times [g_{\mu\nu} - k_\mu k_\nu (2M^2 - k^2) M^{-4}]\,, \tag{12}$$

where M is the average mass of the neutral W's. Note that $k^\mu(K_{\mu\nu}^{(3)} - K_{\mu\nu}^{(2)}) = 2\beta k_\nu / M^2$. This means, roughly speaking, that the production amplitude of neutral leptonic currents in $\Delta S = 1$, $\Delta Q = 0$ hadronic transitions is smaller by a factor 2β than the corresponding amplitude for production of a charged leptonic pair.

The cancellation in Eq. (9) which forbids neutral leptonic currents in $\Delta S = 0 = \Delta Q$ hadronic transitions is independent of the W_2-W_3 mass difference.

Thus, we predict the following new features concerning the leptonic modes for hyperon decays (see Table I) and K decays (see Table II):

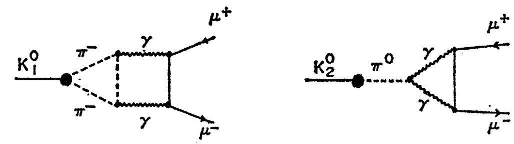
Hyperon decays. The ordinary leptonic decay modes with production of an $e\bar{\nu}_e$ pair are observed with small branching ratio ($\sim 10^{-3}$ or $\sim 10^{-4}$). We predict leptonic decay modes with production of a $\nu_e\bar{\nu}_e$ pair and a branching ratio, with respect to the corresponding charged mode ($e\bar{\nu}_e$), of the order of $4\beta^2$ (up to Clebsch-Gordan coefficients of SU_3). Leptonic decay modes with production of a $\mu^+\mu^-$ pair cannot occur in Λ and Ξ decay because of the lack of available energy, but will occur in Σ decay, with an even smaller rate than $\nu_e\bar{\nu}_e$ decay. (Note that $\Sigma^+ \to p$ transitions are charge-symmetric with respect to $\Sigma^- \to n$, while $\Sigma^+ \to n$ transitions suffer from a wrong $\Delta S/\Delta Q$ sign.)

Hyperon decays into neutral leptonic pairs ($e\bar{e}$) and ($\mu\bar{\mu}$) are also predicted in any conventional weak-coupling theory through the combination of weak and electromagnetic mechanisms. In fact $\Sigma^+ \to p + \gamma$ is observed with a branching ratio of 4×10^{-4}. Thus, one should expect to observe $\Sigma^+ \to p + e^+ + e^-$, through a Dalitz pair, with a branching ratio $\sim 4 \times 10^{-6}$. (The corresponding rate for a $\mu\bar{\mu}$ Dalitz pair will be slightly decreased because of the smaller phase space.)

K decays. The appearance of neutral leptonic currents would be more easily noticed in K decays.

(a) *Two-body decays of K^0-$\bar{K}^0$.* In conventional theories, one expects decays into $\mu^+\mu^-$ pairs through the mechanisms shown in Figs. 6(a) and 6(b). These correspond to branching ratios of $\sim \alpha^4 \simeq 10^{-8}$ for K_1^0 and $\sim 10^{-8}$ for K_2^0.[9]

The $\mu^+\mu^-$ final pair from K decay is either in a ${}^1S_0$ $(CP = -1)$ state or in a ${}^3P_0$ $(CP = +1)$ state. In a conventional theory, with $V - A$ point-like coupling



(a) (b)

FIG. 6. Conventional mechanisms (weak×electromagnetic) for neutral K-meson decays into $\mu^+\mu^-$ pairs.

[9] The decay rate of $K_2^0 \to \mu^+ + \mu^-$ has been estimated by Mirza A. Baqi Bég, Phys. Rev. **132**, 426 (1963). He finds

$$\Gamma(K_2^0 \to \mu^+\mu^-) \lesssim 0.7\ \text{sec}^{-1}.$$

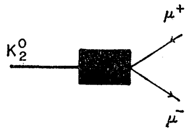


FIG. 7. Point-like coupling of $\mu^+\mu^-$ in K decay.

for the $\mu^+\mu^-$ pair (see Fig. 7), the final state cannot be the ${}^3P_0$ state. Thus, in a conventional CP-invariant theory with neutral leptonic currents, only $K_2{}^0$ decays into $\mu^+\mu^-$. The corresponding experimental branching ratio has a rather small upper limit[10]:

$$\frac{\Gamma(K_2{}^0\to\mu^+\mu^-)}{\Gamma(K_2{}^0\to\text{total})}\lesssim 10^{-4}.$$

In our theory, because of the presence of i in the leptonic coupling, we predict

$$\frac{\Gamma(K_1{}^0\to\mu^+\mu^-)}{\Gamma(K^+\to\mu^+\nu_\mu)}=16\beta^2(\cos^2\theta)\frac{m'}{m}\left(1-4\frac{\mu^2}{m^2}\right)^{1/2}\times\left(1-\frac{\mu^2}{m^2}\right)^{-2},\quad(13)$$

where m' is the $K_1{}^0$-mass, m the K^+ mass, and μ the μ mass. This corresponds to a branching ratio

$$\frac{\Gamma(K_1{}^0\to\mu^++\mu^-)}{\Gamma(K_1{}^0\to\text{total})}=7\beta^2\times10^{-2}.\quad(14)$$

To discuss CP invariance in K^0 decay, it is useful to consider the coherent mixtures $W^{(\mathrm{I})}$ and $W^{(\mathrm{II})}$ of W's which interact with the two proper states of CP:

$$CPK_1{}^0=K_1{}^0,\quad CPK_2{}^0=-K_2{}^0.$$

From Eq. (1) we find

$$K_1{}^0=(K^0-\bar{K}^0)/\sqrt{2}\leftrightarrow W^{(\mathrm{I})}=(1/\sqrt{2})[(W^2-W_2)\sin\theta+(W_3-W^3)\cos\theta]=-W'_A{}^3;$$

$$K_2{}^0=(K^0+\bar{K}^0)/\sqrt{2}\leftrightarrow W^{(\mathrm{II})}=(1/\sqrt{2})\times[(W^2+W_2)\sin\theta+(W_3+W^3)\cos\theta]=W'_S{}^2\sin2\theta+W'_S{}^3\cos2\theta.$$

As we have seen, only the $W'_A{}^2$ is coupled with neutral leptonic currents, and the W_2-W_3 mass difference introduces an off-diagonal element $\frac{1}{2}\beta\sin2\theta$ in the mass matrix of the W'^2-W'^3 system. Hence the $K_1{}^0$ goes to $\mu^+\mu^-$ pair via a $\frac{1}{2}\beta\sin2\theta$ factor in the amplitude, and the $K_2{}^0$ does not.

[10] D. W. Carpenter, A. Abashian, R. J. Abrams, G. P. Fisher, B. M. K. Nefkens, and J. H. Smith, in *Proceedings of the Argonne International Conference on Weak Interactions, 1965*, Argonne National Laboratory Report No. ANL-7130, 1965 (unpublished), p. 98. X. De Bouard, D. Dekkers, B. Jordan, R. Mermod, T. R. Willits, K. Winter, P. Schartt, L. Valentin, M. Vivargent, and M. Bott-Bodenhausen, Phys. Letters **15**, 58 (1965).

(b) *Three-body decays of K^+.* Neutral leptonic currents will appear with a rate ratio

$$\frac{\Gamma(K^+\to\pi^++\bar{\nu}_e+\nu_e)}{\Gamma(K^+\to\pi^0+e^++\nu_e)}=8\beta^2\cos^2\theta\quad(15)$$

and

$$\frac{\Gamma(K^+\to\pi^++\mu^++\mu^-)}{\Gamma(K^+\to\pi^0+\mu^++\nu_\mu)}=3.6\beta^2\cos^2\theta.\quad(16)$$

The corresponding branching ratios are given in Table II. The comparison of the figure given in Eq. (16) with the experimental upper limit[11] yields $\beta\lesssim5\times10^{-3}$.

(c) *Three-body decays of K^0.* Because of the presence of i in the leptonic coupling, $K_1{}^0$ does not decay into $\pi^0+\mu^++\mu^-$ by this mechanism, and we predict the ratio

$$\frac{\Gamma(K_2{}^0\to\pi^0+\mu^++\mu^-)}{\Gamma(K^+\to\pi^++\mu^++\mu^-)}\sim1;\quad(17)$$

hence a branching ratio for $K_2{}^0$:

$$\frac{\Gamma(K_2{}^0\to\pi^0+\mu^++\mu^-)}{\Gamma(K_2{}^0\to\text{total})}=0.5\beta^2.\quad(18)$$

Of course, $K_2{}^0\to\pi^0+\nu_e+\bar{\nu}_e$ is also predicted, with a branching ratio:

$$\frac{\Gamma(K_2{}^0\to\pi^0+\nu_e+\bar{\nu}_e)}{\Gamma(K_2{}^0\to\text{total})}=2.8\beta^2.\quad(19)$$

(*d*) *CP violation.* As we have shown in the preceding section, CP violation can occur only when neutral leptonic currents are involved, and this is not in contradiction with the present experimental situation. In a decay where a $\mu^+\mu^-$ pair is emitted, CP violation is obtained by the competition between a pure weak $\Delta S=1$, $\Delta Q=0$ semileptonic process and a radiative correction of a weak hadronic process. For instance, as can be seen in Table II, $K^+\to\pi^+\mu^+\mu^-$ can occur with a branching ratio $10^{-2}\alpha^2$ (CP-even) and by our neutral leptonic currents with branching ratio $0.12\beta^2$ (CP-odd), so the CP violation in this decay is of the order of $7\alpha\beta/(\alpha^2+12\beta^2)$. This yields a large CP violation if β has a value near the upper limit compatible with present experimental data ($\beta\simeq5\times10^{-3}$).

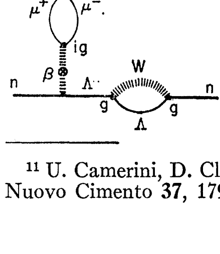


FIG. 8. Electric-dipole-moment mechanism for the neutron ($\beta\neq0$).

[11] U. Camerini, D. Cline, G. Gidal, G. Kalmus, and A. Kernan, Nuovo Cimento **37**, 1795 (1965).

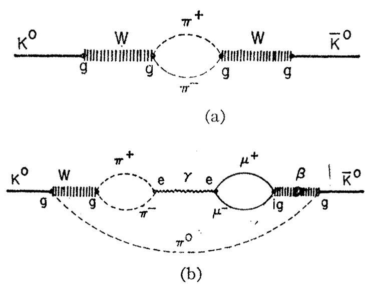


FIG. 9. (a) Diagram contributing to δ in Eq. (21). (b) Diagram contributing to χ in Eq. (21).

For $\beta\neq 0$ an electric dipole moment for the neutron is in principle predicted (see Fig. 8), but it is of order

$$(e/2M_n)(g^4\lambda^{-4}\beta\sin^2\theta)\sim(e/2M_n)(10^{-11}\beta)\,, \quad (20)$$

which is much too small to be detected.

An example of a predicted small CP violation is the $K_2{}^0\to\pi^+ +\pi^-$ decay. As is well known, such an effect has been observed.[4] It can be interpreted by a small imaginary part of $\langle\bar{K}^0|M|K^0\rangle$ in the mass matrix of the K^0-$\bar{K}^0$ complex, where the real part δ gives the mass difference 2δ between $K_1{}^0$ and $K_2{}^0$. The experimentally observed value is

$$2\times 10^{-3}=\left|\frac{\chi}{\delta+i\Gamma_{K_1{}^0}}\right| =\left|\frac{\langle K^0|M|\bar{K}^0\rangle-\langle\bar{K}^0|M|K^0\rangle}{\langle K^0|M|\bar{K}^0\rangle+\bar{K}^0|M|K^0\rangle+i\Gamma_{K_1{}^0}}\right|, \quad (21)$$

where δ and $\Gamma_{K_1{}^0}$ are of the same order of magnitude. A typical contribution to δ is given in the diagram of Fig. 9(a). while the main contribution to χ is probably the one corresponding to the diagram of Fig. 9(b).

The order of magnitude of the ratio ($\sim\alpha\beta$) might seem a little small. However, the predicted theoretical ratio can be smaller than the observed $\Gamma(K_2{}^0\to 2\pi)/\Gamma(K_1{}^0\to 2\pi)$ because the observed $\Gamma(K_1{}^0\to 2\pi)$ rate is slowed down by SU_3 invariance.[12]

VII. EFFECT OF INTRINSIC MAGNETIC MOMENT FOR THE NEUTRAL W's

In this section we study the consequences of the Lagrangian $\mathcal{L}_0+\mathcal{L}_{SU(3)}+\mathcal{L}_W+\mathcal{L}_{\rm em}$ completed by an extra term[13]

$$\mathcal{L}_{\rm em}{}^\mu=\tfrac{1}{2}iF_{\mu\nu}(\sigma_2 W_2{}^\mu W^{2\nu}+\sigma_3 W_3{}^\mu W^{3\nu}\ )\,, \quad (22)$$

which corresponds to magnetic moments $(e\hbar/2M_W c)\sigma_{2,3}$ for the $W_{2,3}$ boson.

The propagator of W^2,

$$(W^2W_2)_{\mu\nu}=(g_{\mu\nu}-k_\mu k_\nu M^{-2})(k^2-M^2)^{-1}\,,$$

can be replaced, when a real photon is emitted by the W, by $\sigma_2 K_{\mu\nu}$, with

$$K_{\mu\nu}=\frac{(q\wedge e)_{\mu\nu}+(e\cdot k)M^{-2}(k\wedge q)_{\mu\nu}-(k\cdot q)M^{-2}(k\wedge e)_{\mu\nu}}{(k^2-M^2)(k^2-2k\cdot q-M^2)}\,, \quad (23)$$

where e and q are the polarization vector and the energy-momentum of the emitted photon and $(a\wedge b)_{\mu\nu}$ means $a_\mu b_\nu-a_\nu b_\mu$. The semileptonic $\Delta S=1$, $\Delta Q=0$ processes with a photon emission are then given by the "phenomenological interaction term"

$$(J^2{}_3)^\mu(\sin\theta\cos\theta)\tfrac{1}{2}(\sigma_2+\sigma_3)K_{\mu\nu}l^\mu\,, \quad (24)$$

where l^ν is the neutral leptonic current $\mu^-\mu^+ +\nu_e\bar{\nu}_e$. Similarly, the $\Delta S=0=\Delta Q$ semileptonic processes now proceed via

$$\tfrac{1}{2}(\sigma_2 J^2{}_2\cos^2\theta+\sigma_3 J^3{}_3\sin^2\theta)^\mu K_{\mu\nu}l^\nu\,. \quad (25)$$

These couplings allow us to compute decays into $\mu^+ +\mu^- +\gamma$ or $\nu_e+\bar{\nu}_e+\gamma$. The most important process is

$$K_2{}^0\to\mu^+ +\mu^- +\gamma\,,$$

which occurs with a branching ratio

$$\frac{\Gamma(K_2{}^0\to\mu^+ +\mu^- +\gamma)}{\Gamma(K_2{}^0\to \text{total})}\simeq 4\lambda^{-4}10^{-3}\,, \quad (26)$$

where $\lambda=M_W/M_p$. Indeed, in the expression for $K_{\mu\nu}$ in Eq. (23), there is a M^{-2} term which will introduce a factor proportional to $\alpha\lambda^{-4}$ in any branching ratio, when $\mu^+ +\nu_\mu+\pi^-$ is replaced by $\mu^+ +\mu^- +\gamma$.

When the photon is reabsorbed, the Feynman diagram becomes divergent. To compute, one must make more assumptions about the dynamics. We shall not make detailed computations here, but simply remark that the replacement of a charged leptonic current by a neutral one is the corresponding semileptonic process introduces a factor α^2 (instead of $4\beta^2$ in the preceding section) in the branching ratio. We have also to note that $K_1{}^0\to\mu^+ +\mu^-$ is not allowed by this mechanism, but $K_2{}^0\to\mu^+ +\mu^-$ is, with a branching ratio of the order of $(\sigma_2+\sigma_3)\alpha^2$, which is to be compared with the experimental upper limit of 10^{-4}.

Particles and antiparticles have opposite magnetic moment. Therefore, by emission of a real or virtual phonon $W_S{}^2$ is changed into $W_A{}^2$ (and conversely). Hence it is the $K_2{}^0$ which decays into γ and a neutral lepton pair (with a $\sin 2\theta$ factor). If the γ is virtual, and reabsorbed by the $\mu^+\mu^-$ pair, then we predict $K_2{}^0\to$

[12] N. Cabibbo, Phys. Rev. Letters 12, 62 (1964); M. Gell-Mann, *ibid.* 12, 155 (1964). See also, R. H. Dalitz, in lectures at the International School of Physics "Enrico Fermi" at Varenna, 1964 (unpublished).

[13] It is well known that one can obtain CP violation by assuming such queer electromagnetic couplings as $\mathcal{L}_{\rm em}{}^Q=\frac{1}{2}\sigma F_{\mu\nu}\times(W_2{}^\mu W_3{}^\nu-W_3{}^\mu W_2{}^\nu)$+H.c., where $F_{\mu\nu}$ is the electromagnetic field. Indeed $W_2{}^\mu W_3{}^\nu-W_3{}^\mu W_2{}^\nu$ is a U-spin singlet which couples W_2 and W_3 bosons, and also couples $W'_2+W'^2$ and $i(W'^2-W'_2)$. However, we do not see the need to be so radical, since a mass difference or an intrinsic magnetic moment of the W's gives the desired effect.

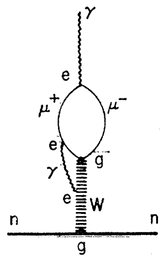


FIG. 10. Electric-dipole-moment diagram for the neutron.

$\mu^+ + \mu^-$ decays. Of course there is a rather negligible probability for the γ to be reabsorbed by the K^0; hence a $K_1^0 \to \mu^+ + \mu^-$ decay is listed in Table II as negligible.

Three-body decays of the K^+ have been well studied experimentally and the upper limit of the branching ratio,

$$\frac{\Gamma(K^+ \to \pi^+ + \mu^+ + \mu^-)}{\Gamma(K^+ \to \text{total})} \lesssim 3 \times 10^{-6}, \tag{27}$$

is comparable to the predicted order of magnitude $\sim 5\alpha^2 \times 10^{-2}(\sigma_2 + \sigma_3)$. So we feel that these last two decays are the best places to look for the appearance of neutral leptonic currents through an intrinsic magnetic moment of neutral W's.

Let us note, however, some other consequences of the intrinsic–magnetic-moment mechanism for $\Delta S = 0 = \Delta Q$ transitions.

It predicts an elastic scattering of ν_e or $\bar{\nu}_e$ which is of order $G^2\alpha^2$, i.e., below the experimental upper limit (which is of course better known for ν_μ).

An electric dipole moment for the neutron is also predicted, for instance by the diagram of Fig. 10. The order of magnitude of the electric dipole moment is

$$(e/2M_n)(g^2\lambda^{-2}\alpha) \simeq 10^{-7}(e/2M_n). \tag{28}$$

Experimentally, the factor of $e/2M_n$ in Eq. (28) is known to be[14] $< 2.3 \times 10^{-6}$. However, new measurements are in progress which could detect such a predicted electric dipole moment.

VIII. CONCLUSION

There is great interest in looking for rare decay modes of hadrons involving neutral leptonic currents. Whatever the underlying theoretical model is, one expects branching ratios for such rare modes to be of the order of the present experimental limits.[15]

In the conventional weak-coupling theories, neutral leptonic pairs are produced electromagnetically through virtual photons. In our scheme, besides this mechanism, neutral leptonic pairs occur through the coupling of neutral leptonic currents. These are coupled in a way similar to that for the charged leptonic currents [i.e., $\bar{\psi} i\gamma^\mu (1 + i\gamma_5)\psi$] but with weaker intensity, except for the purely leptonic processes discussed in Sec. IV.

When the two mechanisms (i.e., the usual one through virtual photons and the one through virtual neutral W's) compete in the production of neutral leptonic pairs, there is CP violation. Thus, a characteristic prediction of our scheme is that except for neutral K decays, CP violation can be observed only in decays where neutral lepton pairs are produced.

Another specific prediction of our scheme is the appearance of $\mu^+\mu^-$ pairs through virtual W's, but not of e^+e^- pairs. This is a consequence of the lepton assignments chosen in Sec. II, which imply that the neutral leptonic current is $\mu^-\mu^+ + \nu_e\bar{\nu}_e$. However, the possibility that consists of changing the roles of μ and e leptons seems also to be compatible with the present experimental data. This was discussed for leptonic processes in Sec. IV(3).

If the neutral leptonic current were $e^-e^+ + \nu_\mu\bar{\nu}_\mu$, then everywhere in Table II the $\mu^+\mu^-$ pair would have to be replaced by an e^+e^- pair with a comparable rate (up to phase-space factors), except for $K_1^0 \to e^+ + e^-$, where the rate should be multiplied by the factor $(m_e/m_\mu)^2$. Furthermore, some new hyperon decay modes (such as $\Lambda^0 \to n + e^+ + e^-$) would be energetically possible.

Finally, although we can only give an order-of-magnitude estimate for the CP violation in $K_2^0 \to \pi^+ + \pi^-$ decay, our prediction that CP violation comes from the K_1^0-K_2^0 mass matrix will be tested when the phase of the CP-violating amplitude is measured.

ACKNOWLEDGMENTS

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[14] J. H. Smith, E. M. Purcell, and N. F. Ramsey, Phys. Rev. **108**, 120 (1957).

[15] See Refs. 10 and 11. See also, U. Camerini, D. Cline, W. F. Fry, and W. M. Powell, Phys. Rev. Letters **13**, 318 (1964).