PHYSICAL REVIEW D VOLUME 2, NUMBER 9 1 NOVEMBER 1970

Possible Nonelectromagnetic Violation of Isospin, Charge-Conjugation, and Time-Reversal Invariance by an Interaction at the Level of Electromagnetism*

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(Received 22 December 1969)

It is proposed that there exists a basic interaction $\mathfrak{L}_V$, not involving the photon, whose strength is similar to that of electromagnetism and which violates isospin, C, CP, and T invariance "maximally," while conserving P and CT. Simultaneously, it is assumed that electromagnetism conserves C, CP, and T. It is proposed that such an interaction arises through the coupling of a vector-meson field $V_\mu{}^0$ to a hadronic current $J_{V\mu}$ with strength g_V comparable to the electric charge e (if V^0 is not too heavy). It is also assumed that V^0 is not involved in other basic interactions (apart from gravity). Some arguments are provided to show that V^0 should be heavier than at least $3m_\pi$. Possible ways of producing and detecting the V^0 meson, which acts as an I-spin schizon like the photon, are discussed. It is suggested that the problem of the sign of the n-p mass difference and that of the forbiddenness of the $\eta \to 3\pi$ decay based on partial conservation of axial-vector current, current algebra, softness of any one pion, and the conventional electromagnetic interaction, may be resolved owing to the existence of the V^0 interaction. A specific model for $\mathfrak{L}_V$, based on Lévy's generalization of the σ model to $SU(3)$, is presented to demonstrate that $\eta \to 3\pi$ forbiddenness is avoided in this model via the contribution of the V^0 interaction. One expects to see (under the proposed hypothesis) noticeable π^+-π^- energy asymmetry in the $\eta \to \pi^+ + \pi^- + \pi^0$ decay, no such asymmetry in the $\eta \to \pi^+ + \pi^- + \gamma$ decay, no noticeable T-violating effects in the $\gamma + d \rightleftarrows n + p$ reactions, and an electric dipole moment of the neutron in the region 10^{-22}–10^{-23} e cm. It is suggested that these measurements should enable us to choose between $\mathfrak{L}_V$ and other existing theories of CP violation.

I. INTRODUCTION AND MAIN IDEA

SINCE the early days of the hypothesis of charge independence, it has often been tacitly assumed that electromagnetism is the only source of violation of isospin, neglecting weak interactions. This assumption is made solely because (a) the photon sees the electric charge and therefore necessarily violates isospin, and (b) the violations of isospin as observed in mass splittings and scattering lengths, etc., are all effects of the order of a few percent in matrix elements, so that in the absence of a first-principles calculation it is natural to associate them with the fine-structure constant $\alpha = e^2/4\pi \approx 1/137$. However, without a complete dynamical theory, there does not seem to be any strong reason to believe that electromagnetism is indeed the only source of violation of isospin apart from weak interactions. We wish to consider in this paper the possibility that there exist interactions[1] not involving the photon, which in general lead to violation of isospin at nearly the same level as the photon. Our motivation for this is based partly on the following observations.

(i) All dynamical attempts for mass-shift calculations based on the notion of emission and absorption of a photon by the hadrons yield the wrong sign for the n-p mass difference. Recently, considerable improvements have been made[2] in these calculations with the inclusion of high-energy contributions[3] and low-mass inelastic contributions[4] to the appropriate dispersion integrals without much success as regards the sign.

(ii) Under the assumptions of partial conservation of axial-vector current (PCAC) and current algebra, the $\eta \to 3\pi$ decay matrix element, presumed to arise through the virtual emission and absorption of a photon, vanishes[5] in the limit of any of the pions becoming soft.[6] On the other hand, experimentally, the $\eta \to 3\pi$ decay seems to have a normal rate (considering that it violates G parity). This situation is rather puzzling[7]

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* Supported in part by the National Science Foundation under Grant No. NSF GP 8748.

[1] Such a possibility was considered earlier by us under somewhat different motivation. See J. C. Pati, Bull. Am. Phys. Soc. **6**, 270 (1961). It is also considered more recently by several authors (mentioned in Ref. 7) from other motivations.

[2] See, in particular, D. Gross and H. Pagels, Phys. Rev. **172**, 1381 (1968); R. Chanda, *ibid.* **188**, 1988 (1969); M. Elitzur and H. Harari, Ann. Phys. (N. Y.) **56**, 81 (1970).

[3] Such contributions have been evaluated by making use of information on electroproduction structure functions as well as finite-energy sum rules for forward γN scattering involving virtual photons. For this purpose see the work of Chanda and of Elitzur and Harari, Ref. 2.

[4] T. Muta, Phys. Rev. **171**, 1661 (1968).

[5] D. G. Sutherland, Phys. Letters **23**, 384 (1966). For a more complete discussion, see also J. S. Bell and D. G. Sutherland, Nucl. Phys. **B4**, 315 (1968). It is to be noted that the vanishing of the $\eta \to 3\pi$ matrix element, as mentioned, of course depends upon assuming that the photon is coupled to the conventional electromagnetic current, which satisfies Gell-Mann's current-commutation relations with the axial-vector currents.

[6] Note that if one assumes that the matrix element for $\eta \to \pi^+ + \pi^- + \pi^0$ decay is well represented by a function linear in the π^0 energy even outside the Daltiz plot up to the points where the various pions are soft, then the matrix element vanishes everywhere if it vanishes when any of the pions is soft. See J. S. Bell and D. G. Sutherland [Nucl. Phys. **B4**, 315 (1968)] for consequences of relaxing such assumptions as linearity.

[7] The problem of $\eta \to 3\pi$ decay has led some authors to propose isospin-violating phenomenological terms of nonelectromagnetic origin in the Lagrangian, which avoid the $\eta \to 3\pi$ forbiddenness. See D. G. Sutherland [Nucl. Phys. **B2**, 433 (1967)], who suggests that the scalar density U_3 [in the notation of M. Gell-Mann, Phys. Rev. **125**, 1067 (1962)] proposed earlier by a number of authors as an effective isospin-violating term in the Lagrangian, may be of nonelectromagnetic origin. A similar idea has also been proposed from quite different standpoints by N. Cabibbo and L. M. Maiani, Phys. Letters **28B**, 131 (1968); and Universita di Roma Instituto di Fisica "G. Marconi," Report, 1969 (unpublished); also R. J. Oakes, Phys. Letters **30B**, 262 (1969). Except for the common feature of nonelectromagnetic isospin violation, the correspondence, if any, of the above works with ours is not clear at present.

in view of the fact that similar assumptions lead to rather good agreement with experiment for the $K \to 3\pi$ decays.[8] Kinematically, the two decays are quite similar.

Although neither of these necessarily calls for a drastic change in our views, they lead us to raise the questions as to whether the *n-p* mass difference is all electromagnetic and whether the violation of G parity necessary to cause the $\eta \to 3\pi$ decay is entirely due to the emission and absorption of a photon. This serves as our motivation for *postulating* a new *basic interaction*, not involving the photon, which in general leads to violation of isospin at the same level as the photon. Since we will assume that this interaction is mediated by a meson to be called the V^0 meson, we will refer to this interaction as the V^0 interaction (in short $\mathcal{L}_V$). In order to narrow our discussion regarding the consequences of this interaction, it is helpful to specify some of its additional properties and conservation laws. These we list below.

(1) $\mathcal{L}_V$ conserves all absolutely conserved quantum numbers such as baryon number, electric charge, and lepton number. It also conserves strangeness, since its strength is comparable to that of electromagnetism.

(2) It violates isospin "maximally." To be somewhat specific regarding its structure and strength, we will assume that it arises through the interaction of a neutral-vector-meson field $V_\mu{}^0$ with a neutral current $J_{V\mu}$ (some of the qualitative consequences of $\mathcal{L}_V$ are preserved under variations of this assumption[9]). If we write the interaction in the form

$$\mathcal{L}_V = -g_V J_{V\mu} V_\mu{}^0\,, \tag{1}$$

we envisage that $g_V{}^2/4\pi$ may be of the order of α, provided V^0 is not too massive,[10] so that virtual emission and absorption of V^0 meson will lead to effects of the same order of magnitude as that of a photon. We will use the symbol α_V for $g_V{}^2/4\pi$. Thus (for not too massive[10] V^0)

$$\alpha_V \equiv g_V{}^2/4\pi \sim 10^{-2}\,. \tag{2}$$

(3) We will assume that the physical V^0 is neither too light nor too massive. We assume that it is not too light (i.e., $m_{V^0} > m_\pi$) primarily because the differences of binding energies of mirror nuclei seem to be well understood on the basis of Coulomb effect. If the V^0 were very light, it would contribute significantly[11] to these differences (assuming $g_V{}^2/4\pi \simeq 10^{-2}$) and spoil the agreement. On the other hand, if m_V is greater than, say, $3m_\pi$-$4m_\pi$, binding energies of nuclei are insensitive to the existence of $\mathcal{L}_V$ with $g_V{}^2/4\pi \simeq 10^{-2}$. In Sec. III we give some additional arguments on experimental grounds to show that the mass of V^0 should be higher than at least $3m_\pi$. We have no *a priori* argument regarding the upper limit on V^0 mass except that from a practical point of view one would prefer that its mass be low enough to allow its production under present means.

(4) We also assume that V^0 is *not involved* in any other[12] basic interaction apart from that given by (1) and gravity. In this case, even though V^0 is coupled to hadrons through the current $J_{V\mu}$, the V^0 interaction may not be regarded as an integral part of the strong interactions to the same extent that electromagnetism is not, and V^0 behaves like an isospin schizon just like the photon.

(5) Furthermore, it is assumed that V^0 is *not directly coupled to leptons*,[13] i.e., $J_{V\mu}$ is composed of hadron

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[8] C. G. Callan and S. B. Treiman, Phys. Rev. Letters **16**, 153 (1966); Y. Hara and Y. Nambu, *ibid.* **16**, 875 (1966); D. K. Elias and J. C. Taylor, Nuovo Cimento **44A**, 518 (1966); H. D. I. Abarbanel, Phys. Rev. **153**, 1547 (1967).

[9] In particular, one may assume $\mathcal{L}_V$ to arise through scalar, pseudoscalar, axial-vector, or tensor interaction without altering much of the qualitative consequences of $\mathcal{L}_V$. Of course, the decay mechanisms of the V^0 meson (see Sec. III) depend upon its spin and parity. We are guided to choose the vector form for $\mathcal{L}_V$ (as against S, P, and T) by our experience with electromagnetic and weak interactions. We have no such specific reason for choice between vector and axial-vector form.

[10] If V^0 is very heavy ($m_V \sim$ a few BeV, say), we expect g_V will accordingly have to be large, so that the effect of a virtual V^0 may still be of the order of α. It is difficult to make quantitative estimates in this respect due to the divergent nature of perturbation calculations. However, a rough dimensional estimate together with the assumption that the perturbation cutoff for any hadron parameter may approximately be given by the $(\text{radius})^{-1}$ of the corresponding interaction (which may lie between a few pion masses to 1 or 2 BeV, say) suggests the following: If V^0 is considerably lighter than the said cutoff parameter$\simeq(\text{radius})^{-1}\equiv\bar{m}$, the effect of a virtual V^0 on mass shifts, etc., is roughly comparable to that of a virtual photon if $g_V{}^2/4\pi \sim \alpha$; on the other hand, if V^0 is considerably heavier than $\bar{m}$, one must require $g_V{}^2/m_V{}^2 \sim e^2/\bar{m}^2 \sim$const, for the two effects to be comparable. In the intermediate mass region, the relationship of g_V to m_V may lie in between.

[11] The contribution of V^0 exchange to the difference of binding energies of H^3 and He^3, for example, may be calculated by taking a potential of the form $(g_V{}^2/4\pi)(e^{-m_V r}/r)$ (for nonrelativistic nucleons) and using the harmonic-oscillator wave function. This leads to a binding-energy difference of nearly 0.35 MeV (for $m_{V^0} \simeq m_\pi$, $g_V{}^2/4\pi \simeq 10^{-2}$, and a size parameter$\simeq m_\pi{}^{-1}$), which is nearly a factor of 10 higher than the maximum possible difference between the observed value and the calculation based on Coulomb effect. On this basis, we may set $m_{V^0} > m_\pi$. It is easy to convince oneself at the same time that the contribution of V^0 exchange to the binding energies decreases rapidly with increasing mass of V^0 (keeping $g_V{}^2/4\pi \simeq 10^{-2}$, fixed); its contribution to binding energies becomes of the same order of magnitude as the errors in experimental measurements and theoretical calculations of Coulomb effects for $m_V \gtrsim 3m_\pi$ (with $g_V{}^2/4\pi \simeq 10^{-2}$). I wish to thank Professor M. K. Banerjee for discussion on this point.

[12] Logically there exists the alternative possibility that V^0 may also share isospin-conserving strong interactions. In this case $\mathcal{L}_V$ may be treated as a small isospin-violating impurity in strong interactions. (I thank Professor C. H. Woo for emphasizing this possibility to me.) I have some prejudice, however, in sticking to the assumption (4) motivated primarily by the fact that so far the known interactions tend to violate a conservation law, if they do, in a maximal way. Of course, from the experimental point of view this choice has more striking possibilities than the alternative one as regards the decay mechanisms of V^0 (see Sec. II). This is because V^0 behaves, like a mixed isospin object, like the photon in our case, whereas with the alternative choice V^0 loses its identity among other strongly interacting objects, all of which are essentially pure isospin states.

[13] There exist some possibilities under which one may allow the coupling of V^0 to leptons. One such obvious possibility is that V^0 is heavy ($m_{V^0} > 3$ BeV may be consistent with all known electron and muon properties, if $g_V{}^2/4\pi \simeq 10^{-2}$). I do not wish to entertain such considerations at present.

fields only. Thus electron-proton scattering is insensitive to $\mathcal{L}_V$. This is one basic difference between the V^0 and the photon.

(6) For the purpose of this paper, we will assume that J_{V_μ} transforms as a U-spin scalar in order to preserve the Coleman-Glashow[14] formula for the baryon octet, which works rather well. (However, the U-spin scalarity of J_{V_μ} may not be an essential requirement if one can find another explanation for the validity of the Coleman-Glashow formula.)

(7) On experimental grounds we must require that $\mathcal{L}_V$ commutes with the parity operation (P) and the product TCP. Similar constraints do not, however, apply to its behavior under the operations of charge conjugation (C) and time reversal (T). To the extent that the origin of CP violation is still unknown, it appears tempting to conjecture that $\mathcal{L}_V$, if it exists, violates C, CP, and T invariance maximally. This attribute appears specially attractive to us if we further assume that electromagnetism[15] conserves C, P, and T, that it may be allowed to maintain its elegance in the minimal form.[16] Subject to this assumption about electromagnetism, we are led to propose that $\mathcal{L}_V$ should violate C, CP, and T by the following purely intuitive reasoning. It appears to us that the existence of every interaction seems to serve some very *specific purpose not served by the others*. It either defines a conservation law or leads to the violation of a conservation law, defined through a stronger interaction, in a maximal way. In addition, each interaction also seems to provide a unique binding force or decay mechanism due to the nature of its strength and conservation laws. These remarks apply to the very strong, the medium strong, the electromagnetic, and the weak interactions. Following this line of intuitive reasoning, it appears that the $\mathcal{L}_V$, if it exists, will be superflous if it violates only isospin but conserves everything else, as electromagnetism[17] does. We are thus led to propose that $\mathcal{L}_V$ *violates* C, CP,[18] *and* T *maximally, in addition to violating isospin. Simultaneously we assume that electromagnetism conserves* C, CP, *and* T. In order for $\mathcal{L}_V$ to violate C, it follows that J_{V_μ} must contain a mixture of C-odd and C-even parts. We thus have[19]

$$\mathcal{L}_V = -g_V(J_{V_\mu}^{(-)}+J_{V_\mu}^{(+)})V_\mu^0\,,$$

where

$$CJ_{V_\mu}^{(\pm)}C^{-1}=(\pm)J_{V_\mu}^{(\pm)}\,. \tag{3}$$

This completes the properties of $\mathcal{L}_V$ which we wish to specify at present.

The following remark is now in order. Even though we have conceived of the new interaction $\mathcal{L}_V$ as a candidate for I-spin violation, once we assign C, CP, and T violation to it, it is clear that these latter features become its primary characteristics. In other words, the new interaction $\mathcal{L}_V$, in addition to providing a mechanism for I-spin violation, serves as a model for C, CP, and T violation as well in the discussion to follow.

In Sec. II we discuss qualitatively some of the consequences of the V^0 interaction. Apart from its implications on the mass shifts and the $\eta \to 3\pi$ decay, we discuss the possible experiments which could distinguish the V^0 interaction as the origin of CP violation from other possible theories of CP violation. In Sec. III, we discuss the decay mechanisms, possible methods of production, and detection of the V^0 particle. We provide some arguments to show that m_{V^0} should be greater than at least $3m_\pi$. In Sec. IV we present an explicit model for the V^0 interaction based on Lévy's[20] generalization of the σ model[21] to $SU(3)$ and demonstrate that the $\eta \to 3\pi$ decay forbiddenness (mentioned before) is avoided in this model. In Sec. V we present a summary and give some remarks.

II. CONSEQUENCES OF V^0 INTERACTION

In this section we list some of the qualitative consequences of the V^0 interaction.

1. Mass Splittings within Isospin Multiplets

As already noted, the contribution of $\mathcal{L}_V$ to mass differences within isotopic multiplets is of the same general order of magnitude as that of electromagnetism.

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[14] S. Coleman and S. L. Glashow, Phys. Rev. Letters **6**, 423 (1961).

[15] It has been proposed by J. Bernstein, G. Feinberg, and T. D. Lee [Phys. Rev. **139**, B1650 (1965)] and S. Barshay [Phys. Letters **17**, 78 (1965)] that electromagnetic interactions of hadrons may violate C, CP, and T invariance maximally. See also subsequent works by T. D. Lee, Phys. Rev. **140**, B959 (1965); **140**, B967 (1965); in *Proceedings of the Third International Symposium on Electron and Photon Interactions at High Energies, Stanford Linear Accelerator Center* (Clearing House of Federal Scientific & Technical Information, Washington, D. C., 1968), p. 390.

[16] T. D. Lee [Phys. Rev. **140**, B967 (1965)] has pointed out, however, that the "minimal" electromagnetic interactions of spin-1 particles can be made noninvariant under C and T in contrast to those of spin-0 and spin-$\frac{1}{2}$ particles.

[17] As mentioned before, we assume to begin with that electromagnetism conserves C, P, and T, although the situation is not clear experimentally.

[18] The general possibility that CP violation may be due to an interaction at the level of electromagnetism, has been pointed out (along with other possible mechanisms for CP violation) by T. D. Lee and L. Wolfenstein [Phys. Rev. **138**, B1490 (1965)]. Their work, however, leaves open a number of questions such as (a) does the new interaction (their H_F) involve the photon; (b) if it does not, does electromagnetism still conserve C, P, and T; (c) does the new interaction violate isospin; if it does, does it lead to an isospin-schizon particle; (d) does it, furthermore, lead to a *CP-conserving* isospin-violating amplitude of order α. Our assumptions (1)–(7) make an *explicit* choice with regard to these questions as well as the space-time structure of the new interaction. Besides, one of our primary motivation to introduce the new interaction $\mathcal{L}_V$ has been to generate a nonelectromagnetic, CP-conserving, and isospin-violating amplitude of order α, which affects significantly the $\eta \to 3\pi$ *rate* and the *n-p* mass difference, for example.

[19] Note that neither the normalization of $J_{V_\mu}^{(-)}$ and $J_{V_\mu}^{(+)}$ nor their relative sign is fixed so far by any *a priori* constraint. I believe, however, that they may be fixed eventually by constraints such as current commutation relations.

[20] M. Lévy, Nuovo Cimento **52A**, 23 (1967).

[21] M. Gell-Mann and M. Lévy, Nuovo Cimento **16**, 705 (1960).

Thus one may only say at present that the existence of $\mathcal{L}_V$ at least provides a scope for possible understanding of the sign of the n-p mass difference. However, the problem remains unresolved until one has a detailed dynamical calculation based on any specific model of $\mathcal{L}_V$.

2. $\eta \rightarrow 3\pi$ *Decay and Problem of Its Forbiddenness*

Since the $\eta \rightarrow 3\pi$ decay necessarily violates G parity, it can proceed in general via the emission and absorption of a photon as well as a V^0 meson. As mentioned before, the photon contribution to the matrix element vanishes on the basis of PCAC, current algebra, and softness[6] of any one of the pions. One would hope that the V^0 contribution, in general, does not suffer the same fate. In Sec. IV we explicitly present a model for $\mathcal{L}_V$, based on Lévy's generalization[20] of the σ model,[21] in which we demonstrate that this is indeed the case. The corresponding amplitude has a nonzero C-conserving part, as well as a C-nonconserving part proportional to the matrix elements of the operators $T(J_{V_\mu}{}^{(+)}(x)J_{V_\nu}{}^{(+)}(0))$ and $T(J_{V_\mu}{}^{(+)}(x)J_{V_\nu}{}^{(-)}(0))$, respectively. The former leads to an $I=1$ final state (in the model[22]) and the latter to a mixture of $I=0$ and 2 final states for the three pions. In our subsequent discussion, we assume that the C-even amplitude has only $I=1$[23] (however, the results are largely unaffected if it has both $I=1$ and 3), and the C-odd amplitude has both $I=0$ and 2.

3. *C Violation in* $\eta \rightarrow \pi^+ + \pi^- + \pi^0$ *Decay*

Since $\mathcal{L}_V$ gives rise in general to an appreciable mixture of C-even and C-odd amplitudes for the $\eta \rightarrow \pi^+ + \pi^- + \pi^0$ decay, we expect to see an asymmetry in the energy distribution of π^+ and π^- owing to an interference between the C-even and C-odd amplitudes. One measure of this asymmetry is given by the parameter

$$A \equiv \frac{N(E_+ > E_-) - N(E_+ < E_-)}{N(E_+ > E_-) + N(E_+ < E_-)}, \tag{4}$$

where $N(E_+ > E_-)$ and $N(E_+ < E_-)$ denote the number of events with π^+ energy greater than and less than that of π^-, respectively. We do not have any reliable estimate of this parameter. However, neglecting the contribution from the $I=0$,[24] C-odd amplitude, a rough estimate for A may be given by[25]

$$|A| \sim |(kR)^2 \sin(\delta_1 - \delta_2)|, \tag{5}$$

where k is the average pion momentum, R is the effective radius of interaction for the C-odd amplitude, and δ_1 and δ_2 are the eigenphase shifts for the three-pion system with total isospin 1 and 2, respectively.

Since k is nearly $0.8m_\pi$, if R^{-1} is in the range[26] $3m_\pi$–$5m_\pi$, A may be expected to be of the order of a few percent. Note that in the electromagnetic theory[15] of CP violation also, A is expected to be of the same order of magnitude,[25] if the C-even electromagnetic current in such a theory contains an $I=1$ part.[27] The recent measurement of A based on 36 800 events yields $A = (1.5 \pm 0.5)\%$.[28] It is clearly of great importance to establish whether this quantity is really different from zero by this order of magnitude.

4. *C Invariance in* $\eta \rightarrow \pi^+ + \pi^- + \gamma$ *Decay*

In processes which involve a photon as an external particle, the leading term in the matrix element is usually of order e. According to our proposal, this is C conserving; C nonconservation arises only in the order $e\alpha_V$, owing to the emission and absorption of a V^0 meson. Thus we predict that the $\eta \rightarrow \pi^+ + \pi^- + \gamma$ decay, for example, should be primarily C conserving with no noticeable asymmetry in the energy distribution of π^+ and π^-. The present experimental value of the $(\pi^+\pi^-)$ energy asymmetry parameter based on 6710 events is $(2.4 \pm 1.4)\%$.[29]

By contrast, in the electromagnetic theory of CP violation one expects[25] to see such an asymmetry. Thus observation of an asymmetry in this decay will clearly establish the latter theory and rule out the particular proposal of ours. However, it has been pointed out by Lee[25] that the lack of any asymmetry in this decay is still consistent with the electromagnetic theory of CP violation, provided one does not allow any $I=0$ or 2, C-even electromagnetic current in such a theory. Thus, even if the $\eta \rightarrow \pi^+ + \pi^- + \pi^0$ decay turns out to possess noticeable asymmetry, and the $\eta \rightarrow \pi^+ + \pi^- + \gamma$ decay

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[22] The general C-conserving amplitude for $\eta \rightarrow 3\pi$ decay leads to both $I=1$ and $I=3$ final states. However, in the model of Sec. IV, the current J_{V_μ} has only $I=0$ and 1 pieces, so that the $I=3$ state cannot be reached via second order in V^0 interaction.

[23] The present experimental branching ratio $\Gamma(\eta \rightarrow 3\pi^0)/\Gamma(\eta \rightarrow \pi^+ + \pi^- + \pi^0)$ is consistent with a pure $I=1$ final state. For a recent experiment, see, for example, C. Baglin *et al.*, Phys. Letters **29B**, 445 (1969).

[24] The $I=0$, C-odd amplitude is expected to be suppressed relative to the $I=2$, C-odd amplitude, since the former leads to a totally antisymmetric (in isospin and therefore space coordinates) three-pion final state and thus is strongly subject to the centrifugal barrier.

[25] T. D. Lee, Phys. Rev. **139**, B1415 (1965); *Proceedings of the Twelfth International Conference on High-Energy Physics, Berkeley, 1966* (California U. P., Berkeley, 1967), p. 75; in *Cargèse Lectures in Physics*, edited by M. Levy (Gordon and Breach, New York, 1966), Vol. 1, p. 55.

[26] If one assumes that the C-odd amplitude may be approximated by the two step process $\eta \rightarrow \rho^0 + \pi^0 \rightarrow (\pi^+ + \pi^-) + \pi^0$, one finds the corresponding $R^{-1} \sim [m_\rho{}^2 - (m_\eta{}^2 - m_\pi{}^2)]^{1/2} \sim 4.6 m_\pi$. [See, for example, B. Barrett, M. Jacob, M. Nauenberg, and T. N. Truong, Phys. Rev. **141**, 1342 (1966).] In the specific model for $\mathcal{L}_V$ presented in Sec. IV, it turns out, however, that the $(\rho\pi)$ intermediate state cannot contribute to the C-odd amplitude. This is directly related to the presence of d_{ijk} coefficients in the C-even current $J_{V_\mu}{}^{(+)}$ [see Eq. (13)].

[27] Of course an $I=3$, C-even electromagnetic current can also lead to the $I=2$, C-odd three-pion state in $\eta \rightarrow 3\pi$ decay. But an $I=3$ electromagnetic current does appear a bit odd.

[28] M. Gormley, E. Hyman, W. Lee, T. Nash, J. Peoples, C. Schultz, and S. Stein, Phys. Rev. Letters **21**, 402 (1968), and references therein.

[29] M. Gormely *et al.*, Phys. Rev. Letters **21**, 399 (1968).

does not, one will still need additional information as, for example, that mentioned below, in order to distinguish between our theory and the electromagnetic theory of *CP* violation.

5. *T Invariance in $\gamma+d\rightleftarrows n+p$ Reactions*

Again, since the photon is involved in these reactions as an external particle, we predict that they should be primarily *T* conserving and therefore satisfy semidetailed balance to a good degree of accuracy. Recently such tests have been made[30] and there seems to be some indication of *T* noninvariance in these reactions. However, they do not seem to be definitive enough to draw any conclusion. It will be of great interest to have conclusive results from these tests. In contrast to our theory, in the electromagnetic theory of *CP* and *T* violation one does generally expect to see large deviations from semidetailed balance in these reactions, unless the *C*-even electromagnetic current does not possess any $I=0$ or $I=1$ piece. (In that case, however, the $\eta\rightarrow\pi^{+}+\pi^{-}+\pi^{0}$ decay energy asymmetry, if found, cannot be accounted for in the latter theory without allowing $I=3$,[27] *C*-even electromagnetic current.)

6. *Electric Dipole Moment of Neutron*

As is well known, the electric dipole moment of the neutron (d_n) is expected in general to be nonzero, provided there exist appropriate mechanisms for *P* and *T* nonconservation. It seems reasonable to assume that the $\Delta S=0$, *CP*-conserving and parity-nonconserving nonleptonic processes may be represented by a coupling strength of the order of $G_F\kappa$, where G_F is the Fermi coupling constant ($G_Fm_p{}^2\simeq10^{-5}$) and κ is a dimensionless constant, whose rough lower limit[31] is $\frac{1}{10}$, say. Thus, purely on dimensional grounds[32] one expects d_n to be

$$d_n\sim e(G_F\kappa)(\epsilon)M\,, \tag{6}$$

where ϵ is a dimensionless quantity characterizing the strength of *T* violation and *M* has the dimension of mass, characterizing roughly the (range)$^{-1}$ of the electric dipole interaction of the neutron. A rough lower limit on *M* may be m_π,[33] and thus $eG_FM\gtrsim3\times10^{-20}$ e cm. If electromagnetism violates *T* invariance, we expect ϵ to be of the order of 1, which would suggest that $|d_n|$ should be roughly greater than or nearly equal to 3×10^{-21} e cm (for $\kappa\gtrsim\frac{1}{10}$). On the other hand, in our theory, ϵ should be of the order of, say, $\alpha_V/\pi\sim1/300$, corresponding to the emission and absorption of a V^0 meson. Therefore, we would expect $|d_n|$ to be roughly greater than or nearly equal to 10^{-23} e cm (for $\kappa\gtrsim\frac{1}{10}$). The most recent experimental value[34] of $|d_n|$ is less than 5×10^{-23} e cm. It is thus consistent with our prediction but seems to disfavor the electromagnetic theory of *C* and *T* violation. (We may note that an electric dipole moment in the range 10^{-22}–10^{-23} e cm is predicted not only by our theory, but also by a number of other theories[35] in which *CP* and *T* violation is assumed to arise through a "small" part in the weak interactions. Thus if $|d_n|$ turns out to be considerably lower than 10^{-23} e cm, it will disfavor all those theories, including ours.)

7. *CP and T Violation in Other Processes Not Involving V^0 Explicitly*

Since we assume that $\mathcal{L}_V$ is the only interaction responsible for *CP* and *T* violation, all processes which do not involve V^0 explicitly (i.e., either externally or virtually in the leading order of the matrix element) are predicted to be primarily *CP* conserving. The *CP*-violating amplitude for all these processes arises through the virtual emission and absorption of a V^0 meson and is thus of order $\alpha_V/\pi\simeq1/300$ compared to the *CP*-conserving amplitude. This is consistent with the observed rate of the $K_L\rightarrow2\pi$ decay compared to that of the $K_S\rightarrow2\pi$ decay. In general, we should also expect a fair mixture of $I=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ pieces in the *CP*-violating $K\rightarrow2\pi$ amplitude, if $J_{V\mu}{}^{(\pm)}$ contain both $I=0$ and 1 pieces. Our predictions in this respect are qualitatively the same as the corresponding predictions of the electromagnetic theory of *CP* and *T* violation for processes not involving the photon explicitly.

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[30] D. G. Bartlett, C. E. Friedberg, K. Goulianos, I. S. Hammerman, and D. P. Hutchison, Phys. Rev. Letters **23**, 893 (1969). Previous preliminary measurement is cited here.

[31] Studies of $\Delta S=0$, *CP*-conserving, but parity-nonconserving transitions in nuclei have established that such interactions exist. [For a review of the experimental and theoretical situation, see, for example, R. J. Blinstoyle, in Proceedings of the Topical Conference on Weak Interactions, CERN, 1969 (unpublished) p. 495.] However, there is no clear picture at present from these studies regarding their basic strength, partly because of the experimental uncertainties and partly also because of the complexity of the interpretation involving complex nuclei. However, if one assumes an usual effective current-current picture for weak interactions, one may obtain the general order of magnitude of the strength of the above-mentioned interactions from that of the observed $|\Delta S|=1$, *CP*-conserving, parity-violating nonleptonic processes such as $\Lambda\rightarrow N+\pi$. [For a discussion of such connections see, for example, B. Tadić, Phys. Rev. **174**, 1694 (1968), and references therein.] One may observe that, while the latter processes may be "enhanced" by the K_1 tadpole mechanism, there is no such corresponding mechanism for their $\Delta S=0$ counterpart (since π^0 and η tadpoles are *CP*-violating). Taking this into account (as well as the fact that the Cabibbo angle $\theta\simeq0.22$) still suggests that the strength of the $\Delta S=0$, parity-violating, and *CP*-conserving nonleptonic amplitudes may be of order $G_F\kappa$ with $\kappa>\frac{1}{10}$.

[32] See, for example, G. Feinberg and H. S. Mani, Phys. Rev. **137**, B636 (1965).

[33] Since the pion is the lightest of all hadrons.

[34] J. K. Baird, P. D. Miller, W. B. Dress, and N. F. Ramsey, Phys. Rev. **179**, 1285 (1969).

[35] For an estimate of d_n in the $V-Ae^{i\phi}$ type of theories, see, for example, P. McNamee, and J. C. Pati, Phys. Rev. **178**, 2273 (1969).

III. MASS, DECAY MECHANISMS, PRODUCTION, AND DETECTION OF V^0 PARTICLE

In this section we discuss possible mass values, allowed decays, production, and possible ways of detection of the V^0 particle. We first discuss the possible decay modes of the V^0 particle under various assumptions about its mass. As noted in Sec. I, considerations based on binding energies of mirror nuclei impose that V^0 should be heavier than a few pion masses.[11] Since there is some uncertainty in the exact value of g_V, however, we attempt in this section to set a lower limit on m_{V^0} on experimental grounds as far as possible.

(i) First, if $m_{V^0}<2m_e$, it will be almost stable except for its allowed slow decay to three photons.[36] In this case, because of its low mass, it could occur as a decay product in processes such as $\omega^0\to\pi^0+V^0$, $\Sigma^0\to\Lambda^0+V^0$, and $\pi^0\to 2V^0$, etc., with branching ratios comparable to those of $\omega^0\to\pi^0+\gamma$, $\Sigma^0\to\Lambda^0+\gamma$, and $\pi^0\to 2\gamma$, respectively. This possibility cannot easily be ruled out experimentally.[36] However, such a low-mass V^0 violating isospin with strength α_V can be quickly ruled out theoretically from considerations of binding energies of mirror nuclei, as mentioned in Sec. I.

(ii) Next, if $2m_e<m_{V^0}<2m_\pi$, then V^0 will still be stable against decay to strongly interacting particles. It can, however, decay dominantly to a (e^-e^+) pair and even to a $(\mu^-\mu^+)$ pair (if $m_{V^0}>2m_\mu$) through the intermediary of a virtual photon (i.e., $V^0\to\gamma\to e^-e^+$). The corresponding rate will be proportional to $\alpha^2\alpha_V\simeq 10^{-6}$; thus the lifetime of the V^0 is expected[37] to be of the order of 10^{-16}–10^{-18} sec (for $m_V\simeq 4m_e\sim 2m_\pi$). However, with m_{V^0} this low, V^0 could still occur in processes such as $\omega^0\to\pi^0+V^0$, and possibly even $\Sigma^0\to\Lambda^0+V^0$ and $\pi^0\to 2V^0$ decays with appreciable branching ratios. In this case, one would have seen decays of the type $\omega^0\to\pi^0+V^0\to\pi^0+(e^++e^-)$, etc., where the (e^-e^+) pair is emitted almost from the production vertex of ω^0 with invariant mass different from zero. We thus rule out essentially on experimental grounds the possibility that $2m_e<m_{V^0}<2m_\pi$.

(iii) For $m_{V^0}>2m_\pi$, V^0 can decay into a number of strongly interacting systems depending upon its mass. In this case, we may ignore its decays to lepton pairs. Some of the allowed dominant decay modes (assuming V^0 is massive enough to decay into these channels) are listed below:

$$
\begin{aligned}
&\text{(a)} \quad V^0\to\pi^++\pi^-\\
&\text{(b)} \quad \to\pi^++\pi^-+\pi^0\\
&\text{(c)} \quad \to K^++K^-\\
&\text{(d)} \quad \to K_L+K_S. \qquad (7)
\end{aligned}
$$

Since we assume the spin-parity of V^0 to be 1^-, V^0 cannot decay to a $2\pi^0$ system by Bose statistics. We note that each of the systems (a), (c), and (d) with $J^P=1^-$ are eigenstates of the charge-conjugation operator with eigenvalue -1. Therefore, these decays must occur only through the C-odd part of $J_{V\mu}$ (i.e., $J_{V\mu}{}^{(-)}$). On the other hand, the $(\pi^+\pi^-\pi^0)$ mode with $J^P=1^-$ can be in both C-odd (with $l_1=l_2=1$) and C-even states (with $l_1=l_2=2$). Thus the $(\pi^+\pi^-\pi^0)$ mode could serve to reveal the C-violating nature of the V^0 interaction. In general, V^0 can also decay to the $(\eta+\pi^0)$ system through $J_{V\mu}{}^{(+)}$ (since the final state has $C=+1$), which, if seen together with any of the C-odd decays (a), (c), or (d), will also establish the mixed C property of V^0. (In the model of Sec. IV, it turns out, however, that $J_{V\mu}{}^{(+)}$ cannot contribute to either the production or the decay of a real V^0 to first order in g_V. See Sec. IV for details.)

As regards the partial widths for the V^0 decay modes, since we assume[38] $\alpha_V=g_V{}^2/4\pi\simeq 10^{-2}$, comparing it with $g_{\rho\pi\pi}{}^2/4\pi\simeq 2$ and $\Gamma(\rho\to\pi\pi)\approx 100$ MeV, we may expect the general order of magnitude of $\Gamma(V^0\to\pi^++\pi^-)$ to be nearly 1 MeV for $m_V\sim m_\rho$. Similarly, we may expect $\Gamma(V^0\to 3\pi)\simeq 10^{-2}\Gamma(\omega\to 3\pi)$ for $m_V\sim m_\omega$ and $\Gamma(V^0\to K\bar{K})\approx 10^{-2}\Gamma(\phi\to K\bar{K})$ for $m_V\sim m_\phi$. In each case, V^0, if it exists and is produced, will appear as a very narrow bump in the corresponding mass measurements.

Having set $m_V>2m_\pi$, we have no strong clue as to the upper limit[39] on the mass of V^0. However, one may still raise the lower limit on it. This is because if, say, $m_V<3m_\pi$, ω^0 could still decay to (π^0+V^0) with appreciable branching ratio[40]; in this case, we would have seen V^0 in the $(\pi^+\pi^-)$ measurement within the ω events corresponding to the two-step process $[\omega\to\pi^0+V^0\to\pi^0+(\pi^++\pi^-)]$. One may, therefore, presume that m_V is greater than at least $3m_\pi$.

Let us now briefly discuss about the possible *production* of V^0. If its mass lies somewhere between, say, $3m_\pi$–$6m_\pi$, it will be possible for some of the heavier mesons to decay into systems involving a V^0 with appreciable branching ratios, especially if the corresponding mode with V^0 replaced by a photon has a relatively large branching ratio. Apart from this possi-

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[36] The rate of $V^0\to 3\gamma$ decay is expected to be extremely slow for $m_{V^0}<2m_e$ owing to the large centrifugal barrier together with the small phase space. A very conservative estimate yields $\tau_{V^0}>10^4$ sec for $m_{V^0}<2m_e$. In this case, one hardly expects to see a real V^0 via its decay to three photons followed by conversion of the photons to (e^-e^+) pairs.

[37] For this purpose, we must of course assume that m_{V^0} is not too close to $2m_e$ to allow enough phase space for the decay. The possibility of m_{V^0} close to $2m_e$ is ruled out again from considerations of binding energies of mirror nuclei.

[38] It is perhaps worth noting that in general one expects strong interactions to modify the effective V^0-decay coupling constants. However, in the model of Sec. IV, $J_{V\mu}{}^{(-)}$ is a conserved current. Thus to lowest order in g_V and all orders in strong interactions, there is no renormalization of g_V at the V^0-decay vertex in the model.

[39] The precise determination of ρ^0 and ω^0 decays to lepton pairs together with a study of the $\rho^0-\omega^0$ mixing parameter may give us some information on the V^0 mass (for an assumed g_V).

[40] We note that the phase space for $\omega^0\to\pi^0+\gamma$-decay is bigger than that of the $\omega^0\to\pi^0+V^0$ decay by nearly a factor of 3 for $m_V=3m_\pi$ and a factor of 20 for $m_V=4m_\pi$.

bility, V^0 can be produced in many reactions, such as

$$\begin{array}{ll}
\text{(a)} & \pi+N\to N+V^0 \\
& \qquad\qquad\quad\searrow \\
& \qquad\qquad\qquad \pi^++\pi^-, \\
\text{(b)} & K^-+p\to\Lambda+V^0 \\
& \qquad\qquad\quad\searrow \\
& \qquad\qquad\qquad \pi^++\pi^-, \\
\text{(c)} & \bar{p}+p\to\pi^++\pi^-+V^0 \\
& \qquad\qquad\qquad\qquad\searrow \\
& \qquad\qquad\qquad\qquad\quad \pi^++\pi^-, \\
\text{(d)} & d+d\to\text{He}^4+V^0 \\
& \qquad\qquad\quad\searrow \\
& \qquad\qquad\qquad \pi^++\pi^-,\quad\text{etc.}
\end{array}\tag{8}$$

We have indicated in each case that V^0, having been produced, decays via the $(\pi^+\pi^-)$ mode, since that is expected to be its dominant decay mode at least for, say, $m_V<1200$ MeV. However, it could also decay into the other channels [listed in Eq. (7)], depending upon its mass.[41] For any of these reactions sufficiently above the threshold for the production of V^0, we expect the cross section to be roughly α_V ($\simeq 1/100$) times smaller than those of the corresponding processes with V^0 replaced by the strongly interacting vector mesons[42] ρ^0, ω^0, and ϕ, etc. Since ϕ production with a rather "small" cross section in reaction (b) is easily detectable under the present means, we hope that V^0 production, if it exists, may also be detectable through the $(\pi^++\pi^-)$ mass measurement [or even (K^++K^-) mass measurement if V^0 is massive enough[41]] in the (K^-+p) reactions. In this sense, existing measurements in the (K^-+p) processes may set some limits on V^0 production. The production and detection of V^0 in πN reactions may have the problem[43] of large background.

We have added the $d+d\to\text{He}^4+V^0$ reaction to the list, because if we observe V^0 in this reaction through the $(\pi^++\pi^-)$ mass measurement and can establish that it has $J^P=1^-$, and that there does not exist any charged counterparts of V^0 decaying to $(\pi^\pm+\pi^0)$ systems, it will be a direct demonstration of the *mixed isospin character* of V^0, since in the production it must have $I=0$, while in the decay to $(\pi^++\pi^-)$ with $J^P=1^-$ it must have $I=1$. The expected cross section for the above effective isospin-violating reaction [i.e., $d+d\to\text{He}^4+V^0\to\text{He}^4+(\pi^++\pi^-)_{1^-}$] is of order α_V rather than α^2; thus it is not too small.[44]

In any case, we note that the detection of an object through a narrow peak in the $(\pi^++\pi^-)$ mass measurement together with lack of charged counterparts in the $(\pi^\pm+\pi^0)$ mass measurements would be rather interesting, if one can further establish that the object thus seen has $J^P=1^-$ and that the $(\pi^++\pi^-)$ mode is one of its dominant decay modes. This will again unambiguously exhibit the mixed isospin character of the object seen and will thus establish that it is the V^0 proposed here. (See Note added in proof).

IV. MODEL FOR V^0 INTERACTION

In this section we present an explicit model of the V^0 interaction ($\mathfrak{L}_V$) based on the idea proposed in Sec. I and demonstrate in the model that the contribution of $\mathfrak{L}_V$ to the $\eta\to 3\pi$ decay does not suffer from the same forbiddenness (mentioned in Sec. I) as that of electromagnetism. We hope to discuss further consequences of this model elsewhere. Needless to say, the model is by no means unique,[45] and the consequences derived may be more general than the model.

We base our choice of $\mathfrak{L}_V$ on Lévy's[20] generalization of the σ model[21] to $SU(3)$, since it satisfies PCAC[46] and Gell-Mann's current algebra.[47] The model is built[48] out of a triplet of quark fields q, their Hermitian conjugates $q^\dagger$, a nonet of pseudoscalar fields π_i and a nonet of scalar fields σ_i. We refer the reader to Lévy's paper[20] for an explicit structure of the Lagrangian $\bar{\mathfrak{L}}$ based on $SU(3)$-symmetric[49] and $SU(3)$-breaking but isospin-conserving interactions.

We write down only the structure of those vector and axial-vector currents in the model whose components participate in the electromagnetic and weak interactions. They are

$$\mathfrak{F}_\mu{}^k=\bar{q}\gamma_\mu(\tfrac{1}{2}\lambda_k)q+f_{ijk}(\pi_j\partial_\mu\pi_k+\sigma_j\partial_\mu\sigma_k)\tag{9}$$

and

$$\mathfrak{F}_{\mu5}{}^k=\bar{q}\gamma_\mu\gamma_5(\tfrac{1}{2}\lambda_k)q+d_{ijk}(\sigma_j\partial_\mu\pi_k-\pi_j\partial_\mu\sigma_k)\,,\tag{10}$$

---

[41] For example, if $m_V\simeq 1500$ MeV, then the phase space for the $V^0\to K\bar{K}$ decay mode is nearly 40% of that for the $V^0\to\pi^++\pi^-$ decay mode. The effective coupling constants for decay to $(\pi^+\pi^-)$ and (K^+K^-) mode are comparable. They are exactly equal in the limit of $SU(3)$ and the model of Sec. IV.

[42] Of course, we should bear in mind the fact that the cross sections for the production of ρ, ω^0, and ϕ differ considerably in most reactions.

[43] This is specially so if V^0 is not massive enough ($m_V<1200$ MeV, say), so that its decay to $(K+\bar{K})$ modes is inhibited.

[44] Note that ω production via $d+d\to\text{He}^4+\omega^0$ has been observed with a cross section $\sim$a few$\times 10^{-33}$ cm^2 through missing-mass measurement. See H. J. Martin, R. R. Crittenden, and L. S. Schroeder, Phys. Letters **22**, 352 (1966); A. Barbaro-Galtieri, M. Matison, A. Rittenberg, and F. T. Shively, LRL Report No. UCRL-17914, 1967 (unpublished); R. Barloutaud *et al.* (SABRE Collaboration), Phys. Letters **26B**, 674 (1968).

[45] The choice of $\mathfrak{L}_V$ clearly depends in the first place on the choice of the basic fields and the corresponding structure of the basic Lagrangian $\bar{\mathfrak{L}}$ without additional interactions such as $\mathfrak{L}_V$. However, even with a given set of basic fields and $\bar{\mathfrak{L}}$, the choice of $\mathfrak{L}_V$ or equivalently of $J_{V\mu}$ has sufficient freedom. This is in contrast to the choice of the electromagnetic current for a given $\bar{\mathfrak{L}}$, and is at least partly related to the fact that we have not required $J_{V\mu}$ to be a conserved current and partly due to the fact that its normalization (or the normalization of $J_{V\mu}{}^{(-)}$ and $J_{V\mu}{}^{(+)}$ separately) has not been constrained by any *a priori* constraint such as current commutation relations, as mentioned in Ref. 19. We hope to investigate such questions in a subsequent work.

[46] PCAC is satisfied to the extent that one does not add additional interactions such as electromagnetism and $\mathfrak{L}_V$, etc.

[47] M. Gell-Mann, Phys. Rev. **125**, 1067 (1962).

[48] Lévy's model can also include a nonet of vector and a nonet of axial-vector mesons, which we exclude for simplicity.

[49] See also S. L. Adler and R. F. Dashen, *Current Algebras and Applications to Particle Physics* (Benjamin, New York, 1968), p. 24, for a discussion of Lévy's model with no $SU(3)$ breaking.

where the indices i, j, k run over $(0,1,\ldots,8)$; the coefficients f_{ijk} and d_{ijk} are defined by Gell-Mann[47] [in particular, $d_{0ij}=(\sqrt{\tfrac{2}{3}})\delta_{ij}$ and $f_{0ij}=0$]; the λ_k's are 3×3 matrices, also defined by Gell-Mann,[47] with $\lambda_0=(\sqrt{\tfrac{2}{3}})\mathbf{1}$. Lévy[20] has shown that these currents satisfy PCAC and Gell-Mann's current commutation relations[47] with his choice of the Lagrangian $\bar{\mathfrak{L}}$. We wish to add to the Lagrangian $\bar{\mathfrak{L}}$ proposed by him, the V^0 interaction term $-g_V J_{V\mu} V_\mu{}^0$ together with the free term for the V^0 field. The source $J_{V\mu}$ of $V_\mu{}^0$ is to be constructed out of the same basic fields as $\bar{\mathfrak{L}}$. Subject to the assumptions (6) and (7) of Sec. I, we choose the C-odd and C-even parts of $J_{V\mu}$ as follows:

$$J_{V\mu}{}^{(-)}=\tfrac{1}{2}\bar{q}\gamma_\mu(\lambda_3+\lambda_8/\sqrt{3})q + (f_{3km}+f_{8km}/\sqrt{3})(\pi_k\partial_\mu\pi_m+\sigma_k\partial_\mu\sigma_m) \quad (11)$$

and

$$J_{V\mu}{}^{(+)}=d_\mu{}^3+(1/\sqrt{3})d_\mu{}^8\,, \quad (12)$$

where

$$d_\mu{}^i(x)\equiv d_{ijk}(\pi_j\partial_\mu\pi_k-\sigma_j\partial_\mu\sigma_k)\,. \quad (13)$$

The total current is

$$J_{V\mu}=J_{V\mu}{}^{(-)}+J_{V\mu}{}^{(+)}\,. \quad (14)$$

Thus $J_{V\mu}{}^{(-)}$, as chosen, is *identical* to the electromagnetic current (except for the term proportional to e containing the photon field); it is *conserved* in the absence of interactions such as $\mathfrak{L}_{\text{em}}$ and $\mathfrak{L}_V$ and is odd under C. On the other hand, $J_{V\mu}{}^{(+)}$ is even under C and is *not conserved.*[50] It is easy to see that both $J_{V\mu}{}^{(-)}$ and $J_{V\mu}{}^{(+)}$ transform as U-spin scalars as required by our assumption (6) of Sec. I. The *negative sign* between the $\pi_j\partial_\mu\pi_k$ and $\sigma_j\partial_\mu\sigma_k$ terms in (13) is chosen to avoid the problem of $\eta\rightarrow3\pi$ forbiddenness, as explained below.

In order to apply the soft-pion technique to the $\eta\rightarrow3\pi$ decay, we derive the following commutation relation using Eqs. (10), (12), and (13):

$$[F_5{}^a(t),d_0{}^j(\mathbf{x},t)] =(-i)(d_{aml}d_{jmk}+d_{amk}d_{jml})(\pi_k\partial_0\sigma_l+\sigma_l\partial_0\pi_k)\,, \quad (15)$$

where

$$F_5{}^a(t)=\int d^3y\,\mathfrak{F}_{05}{}^a(\mathbf{y},t)\,. \quad (16)$$

It is easy to verify that the right-hand side of (15) is a mixture of $I=1$ and 2 operators for $j=3$ and $a=1$ or 2; it is a mixture of $I=0$ and 2 operators for $j=3$ and $a=3$, while it is a non-null $I=1$ operator for $j=8$ and $a=1$, 2, or 3. *In contrast,* if $d_0{}^j(\mathbf{x},t)$ is replaced by the electromagnetic charge density $J_0{}^{\text{em}(j)}(t)$ ($j=3$ or 8) in the left-hand side of (15), the corresponding commutator has no $I=0$ or 2 operators for $j=3$ and $a=1$, 2, or 3; while it vanishes for $j=8$ and $a=1$, 2, or 3. One may now convince oneself that the presence of $I=0$ and/or 2 operators in the commutator (15) for $j=3$ as well as the nonvanishing of the commutator for $j=8$ (with $a=1$, 2, or 3 in either case) leads to *nonvanishing contribution* from $\mathfrak{L}_V$ to the $\eta\rightarrow3\pi$ matrix element in second order, subject to the constraints of PCAC, current commutation relations, and softness of the ath pion. The nonvanishing contribution corresponds to matrix elements of the terms $T(J_{V\mu}{}^{(+)}(x)J_{V\nu}{}^{(+)}(0))$ as well as $T(J_{V\mu}{}^{(+)}(x)J_{V\nu}{}^{(-)}(0))$. The former leads to C-even amplitude and the latter to C-odd amplitude. The contribution of the term $T(J_{V\mu}{}^{(-)}(x)J_{V\nu}{}^{(-)}(0))$, however, vanishes in the soft-pion limit for the same reason as that of electromagnetism.

We may now comment on the choice of the negative sign between $\pi_j\partial_\mu\pi_k$ and $\sigma_j\partial_\mu\sigma_k$ terms in Eq. (13). If we had chosen a positive sign instead, we would have obtained a difference of the product of two d coefficients on the right-hand side of (15) instead of their sum. Such a difference can be expressed as a product of two f coefficients, which leads to the same isospin properties of the commutator (15) as that of the corresponding commutator with $d_0{}^j$ replaced by $J_0{}^{\text{em}(j)}$ in (15). Thus one will have the same forbiddenness for the contribution of $\mathfrak{L}_V$ to the $\eta\rightarrow3\pi$ decay as that for $\mathfrak{L}_{\text{em}}$. We therefore choose the negative sign in Eq. (13).

Another property of our choice of $\mathfrak{L}_V$ is worth noting. Let us write the V^0-interaction term in the Lagrangian as

$$\mathfrak{L}_V=-g_V(J_{V\mu}{}^{(-)}+J_{V\mu}{}^{(+)})V_\mu{}^0 =\mathfrak{L}_V{}^{(-)}+\mathfrak{L}_V{}^{(+)}\,, \quad (17)$$

where

$$\mathfrak{L}_V{}^{(\pm)}=-g_VJ_{V\mu}{}^{(\pm)}\,. \quad (18)$$

We may write $\mathfrak{L}_V{}^{(+)}$, in turn, as follows:

$$\mathfrak{L}_V{}^{(+)}=-g_VJ_{V\mu}{}^{(+)}V_\mu{}^0=-g_V(d_{3km}+(1/\sqrt{3})d_{8km}) \times(\pi_k\partial_\mu\pi_m-\sigma_k\partial_\mu\sigma_m)V_\mu{}^0 \quad (19)$$

$$=-\tfrac{1}{2}g_VV_\mu{}^0(d_{3km}+(1/\sqrt{3})d_{8km})\partial_\mu(\pi_k\pi_m-\sigma_k\sigma_m) \quad (20)$$

$$\sim+\tfrac{1}{2}g_V[(d_{3km}+(1/\sqrt{3})d_{8km}) \times(\pi_k\pi_m-\sigma_k\sigma_m)]\partial_\mu V_\mu{}^0\,. \quad (21)$$

The symbol $\sim$ signifies that expressions (20) and (21) are equivalent from the point of view of the equations of motion, since they differ from each other by the total derivative of a term. Using the form (21), it is clear that $\mathfrak{L}_V{}^{(+)}$ cannot lead to either the production or the decay of a real V^0 to first order[51] in g_V, since the matrix

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[50] If only bilinear combinations of spin-0 and spin-$\tfrac{1}{2}$ fields enter into $J_{V\mu}$, it is not easily feasible to have its C-even part conserved. (Such conservation may be made possible in a limited sense by adding for example, additional scalar and pseudoscalar multiplets. I thank Professor M. Lévy for pointing this out to me.) However, with spin-1 fields, it is possible to construct a C-even conserved vector current as, for example, proposed by T. D. Lee (Ref. 15) and S. L. Adler, Phys. Rev. Letters **18**, 519 (1967). It is also possible to have the C-even part of $J_{V\mu}$ at least partially conserved in models such as the Han-Nambu three-triplet model by generating $J_{V\mu}{}^{(+)}$ through allowed additional symmetries in the model. This is to be discussed in a forthcoming paper.

[51] Even, to higher orders in g_V, $\mathfrak{L}_V{}^{(+)}$ alone cannot contribute to the production and decay of a real V^0; it can contribute only by

element in this case is proportional to $k_\mu{}^V\epsilon_\mu{}^V=0$, where $k_\mu{}^V$ and $\epsilon_\mu{}^V$ are the momentum and polarization four-vectors of the V^0 particle. Thus, to first order in g_V, the production and decay of a real V^0 take place only through the C-odd current $J_{V\mu}{}^{(-)}$ (in the present model of $\mathfrak{L}_V$).

V. SUMMARY AND REMARKS

It is proposed in this paper that there exists a basic interaction $\mathfrak{L}_V$, not involving the photon, whose strength is similar to that of electromagnetism and which violates isospin, C, CP, and T invariance "maximally," while conserving P and CT. Simultaneously, it is assumed that electromagnetism conserves C, CP, and T. It is assumed that such an interaction arises through the coupling of a vector-meson field $V_\mu{}^0$ to a hadronic current $J_{V\mu}$ with strength g_V, which is comparable to the electric charge e (if V^0 is not too heavy[10]). It is also assumed that V^0 is not involved in any other basic interaction (apart from gravity). It is noted that the existence of such an interaction is not inconsistent with the known degree of validity of charge independence provided V^0 is not too light[11] ($m_{V^0}>$ few pion masses, say). Certain other considerations (see Sec. III) based on the decays of known objects require that V^0 should be heavier than at least $3m_\pi$.

It is discussed (in Sec. III) that the V^0 meson may be produced in processes such as $(\pi+N)$, (K^-+p), and $(d+d)$ reactions, etc., with cross sections nearly 100 times smaller than those of the ρ^0, ω^0, and ϕ^0 productions, provided the incident energies are sufficiently above thresholds for the production of V^0. The V^0 meson, if produced, would decay dominantly to the $(\pi^++\pi^-)$ system at least for $m_{V^0}<1200$ MeV; it will also decay to other systems such as $(\pi^++\pi^-+\pi^0)$ and $(K\bar{K})$ systems depending upon its mass.[41] In each case, it will appear as a very narrow bump $[\Gamma(V^0\to\pi^++\pi^-)\lesssim 1\text{ MeV}]$ in the corresponding mass measurements. It is noted that the observation of a state decaying dominantly to a $(\pi^+\pi^-)$ system with $J^P=1^-$ together with lack of any charged counterparts will be rather *interesting*, since that will unambiguously determine that the object thus seen has mixed isospin character.

It is suggested that the existence of $\mathfrak{L}_V$ may help understand the observed sign of the $(n\text{-}p)$ mass difference, although we have no dynamical calculation based on any specific model for $\mathfrak{L}_V$ to support this hope at present. It is also proposed that the problem of the $\eta\to 3\pi$ forbiddenness based on PCAC, current algebra, softness of any one of the pions, and conventional electromagnetic interactions may be resolved due to the presence of the V^0 interaction. In Sec. IV, we propose a specific model for $\mathfrak{L}_V$ based on Lévy's generalization of the σ model to $SU(3)$, in which we demonstrate that this is indeed the case.

As regards the C-, CP-, and T-violating properties of $\mathfrak{L}_V$, it is discussed in Sec. III that accurate results of the following tests (or measurements) could very well choose between $\mathfrak{L}_V$ and other existing theories of CP violation: (a) the test of C invariance in the $\eta\to\pi^++\pi^-+\pi^0$ decay, (b) that in the $\eta\to\pi^++\pi^-+\gamma$ decay, (c) the test of T invariance in $\gamma+d\rightleftarrows n+p$ reactions, and (d) the magnitude of the electric dipole moment of the neutron.

If it turns out that there is some general truth about the existence of $\mathfrak{L}_V$ (defined in Sec. I), the following questions may deserve further study: (a) the question of the conservation[52,53] or nonconservation of $J_{V\mu}{}^{(\pm)}$ and of $J_{V\mu}$; (b) the problem of the normalization of $J_{V\mu}{}^{(\pm)}$, which may be related to its commutation properties with other currents; and (c) the correspondence, if any, of the idea proposed here with that of others[54] who propose effective isospin-violating terms of nonelectromagnetic origin in the Lagrangian from other considerations.

Note added in proof. After this paper was written, I noticed a report by L. Dubal and M. Roos in the Proceedings of the Conference on $\pi\pi$ and $K\pi$ interactions, edited by F. Loeffler and E. Malamud, Argonne National Laboratory Report, page 285 (unpublished), where they report a 5-standard-deviations 25-μb enhancement at (482 ± 3) MeV in a compiled $(\pi^+\pi^-)$ mass distribution from $\pi^-+p\to\pi^-+\pi^++n$. The width of this object is reported to be less than 25 MeV and it is also noted that it does not seem to have any charged counterparts. The authors give additional arguments to suggest that this object may be an $I=J=0$ $(\pi\pi)$-resonance rather than a $I=0$, $J=$odd system decaying electromagnetically via the $(\pi^+\pi^-)$-mode since in the latter case it ought to have shown up before in other experiments. I wish to comment that if this object is real, it is unlikely to be an $I=J=0$ object, since in this case it is expected to make large contribution with the wrong sign to the (K_L-K_S) mass difference compared to the observed value due to the fact that it lies so close but lower than the K^0 meson and has spin zero. On the other hand, if it is the spin-1 V^0 meson as proposed here, then in the first place it makes negligible contribution to the (K_L-K_S) mass difference [since in this case the denominator $(m_K{}^2-m_V{}^2)$ of the V^0-meson propagator gets cancelled by the same factor appearing in the numerator; the V^0 contribution to the mass difference is further reduced by the factor $g_V{}^2/4\pi$.] In the second

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letting $\mathfrak{L}_V{}^{(-)}$ act also. This point became clear in discussions with Professor M. Lévy and Professor J. Sucher.

[52] See remarks in Ref. 50.

[53] We may note that the photon is distinguished by the fact that it is coupled to the conserved electromagnetic charge. The question of conservation of $J_{V\mu}{}^{(\pm)}$, or of $J_{V\mu}$, derives its importance from the question of the corresponding distinction of the V^0 meson, if any. Furthermore, if $J_{V\mu}$ was conserved, the theory will be renormalizable.

[54] We have in mind the works of Cabibbo and Maiani and Oakes (for example), Ref. 8.

place the small production cross section of the above object (which is nearly 1% of that of the ρ^0 meson) and its small width are both consistent with its being the V^0 meson, since both are proportional to $g_V^2/4\pi \simeq 10^{-2}$. Thus if the above effect is confirmed, it appears to be a likely candidate for the V^0 meson proposed here. In this case its width should lie in the region of 1 MeV and the effect should be absent in the $(\pi^0\pi^0)$ system. A careful study of the $(\pi\pi)$ system in the above mass region should thus be very useful.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge my gratitude to Professor M. Lévy, Professor G. A. Snow, Professor O. W. Greenberg, and Professor C. H. Woo for most helpful discussions, for their comments and interest in this work. I have benefited from much helpful conversations with Dr. R. Chanda, Professor B. Kehoe, and Professor J. Sucher. I am indebted to Professor M. K. Banerjee for a discussion on the binding energies of mirror nuclei.

PHYSICAL REVIEW D VOLUME 2, NUMBER 9 1 NOVEMBER 1970

Meson-Baryon Interactions with Broken $SU(3)$ and the Baryon Spectrum in Relativistic Quantum Mechanics*

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(Received 22 April 1970)

The multichannel relativistic Schrödinger equation is solved for the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ partial-wave amplitudes and their Regge recurrences with an energy-dependent potential obtained by computing the baryon-exchange contribution to the pseudoscalar-meson–baryon interaction. As discussed previously, the model yields the usual $\frac{3}{2}^+$ decuplet and predicts in addition a 27-dimensional representation and a radially excited decuplet in this partial wave. It is shown that in the range of parameters which fit the usual decuplet, there are also decuplet orbital excitations in the $\frac{7}{2}^+$ and $\frac{11}{2}^+$ partial-wave amplitudes which correspond to the known experimental resonances. The $\frac{1}{2}^+$ octet is obtained as deeply bound states, and a second $\frac{1}{2}^+$ octet or a $\overline{10}$ representation is predicted, depending on whether the F/D ratio is less than or greater than 0.34. In addition, an orbital excitation of the octet occurs in the $\frac{5}{2}^+$ partial-wave amplitude at very high energies. The P-wave phase shifts are in qualitative agreement with experiments, but there are deviations for the P_{33} effective range near threshold and for the P_{13} phase shifts at higher energies.

I. INTRODUCTION

In this paper we study the baryon spectrum by solving the multichannel relativistic Schrödinger equation with a potential obtained by computing the baryon-exchange contribution to pseudoscalar meson-baryon scattering. We perform the off-shell extrapolation in such a way that no cutoff is needed. $SU(3)$ relations are assumed for the coupling constants and physical masses for the input particles. Hence our calculations depend on two parameters: the pion-nucleon coupling constant and the F/D ratio. As discussed in Refs. 1–3, the relativistic Schrödinger multichannel equation may be used in dynamical calculations, since the principles of relativistic invariance, unitarity, and analyticity or causality are satisfied and there are no difficulties in dealing with the multichannel problem. In fact, this equation might even be preferred to other techniques based on the N/D method since it includes iterations of the potential.

Following Gell-Mann's pioneering eightfold-way approach,[4] most papers on baryon resonances deal only with their group-theoretical classification and do not contain any detailed dynamics. On the other hand, dynamical calculations (such as Chew's first calculation of the $N_{3/2}{}^*$ resonance[5]) deal usually with only one channel or introduce a second channel purely phenomenologically[6] and thus neglect any internal symmetry group. Obviously, many features of the physical baryon spectrum only become clear if one studies models containing both dynamics and an internal symmetry group (as first discussed in Ref. 7). For example, $SU(3)$ group theory tells us in our case (interaction of two octets) that resonances or bound states may be present

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* Work supported in part by the Deutsches Elektronen-Synchrotron DESY, Deutsche Forschungsgemeinschaft, and the U. S. Atomic Energy Commission.

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