# *A MODEL OF VIOLATED ISOTOPIC SYMMETRY FOR A UNIFIED ELECTROMAGNETIC-WEAK INTERACTION OF HADRONS*

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The possibility of constructing a model of unified electromagnetic-weak interaction of hadrons with violated isotopic symmetry is investigated. The vanishing of the photon mass and parity conservation by electromagnetism occur as a consequence of the violation of the symmetry of the primary unified isotopic- and CP-invariant interaction, due to the mixing of vector bosons belonging to different isotopic multiplets. The known empirical selection rules for the weak interactions of hadrons and their minimal electromagnetic interactions appear as special manifestations of broken symmetry at low energies. The interesting effect of the restoration of the broken symmetry for large 4-momentum transfer in the $e^2$-approximation of perturbation theory is discussed.

## 1. INTRODUCTION

THE model of weak interactions with intermediate vector bosons seems to be the only model compatible with the hope of constructing a unified electromagnetic-weak interaction. The concept of unified electromagnetic-weak interaction has been developed earlier by Schwinger,[1] Ya. B. Zel'dovich (private communication), Salam and Ward[2] and Glashow[3].* This concept assumes that the constant of semiweak interactions is equal to the electric charge ($g = e$), the mass of the intermediate boson is large $M \sim (e^2/G)^{1/2} \sim 30$ GeV (here G is the Fermi coupling constant), the electric current being the neutral partner of the charged weak interaction currents. The latter point of view has been developed further in [4], where it was assumed that the electric current and the strangeness conserving weak currents (both charged and neutral) together form a complete set of components of an isovector and isoscalar (the hypercharge current).

The vanishing of the photon mass and parity conservation in electromagnetic interactions were two well-known difficulties of this approach. It is conceivable that an understanding of these difficulties can come only from the concepts of broken symmetry, concepts which in recent years have acquired an increasing importance, especially in connection with the successes of the classification of hadrons.[5] It is without doubt interesting to investigate possibilities of this sort on the example of concrete models of unified electromagnetic-weak interactions.

In the present paper the possibility of constructing a model of unified electromagnetic-weak interaction of hadrons is investigated, by means of a generalization of the previously proposed model of violated isotopic symmetry in the weak interactions of hadrons.[6,7] Within the framework of this model one can overcome both mentioned difficulties and at the same time avoid contradicting the presently known experimental data on weak interactions and electromagnetic phenomena, via the introduction of a larger number of intermediate vector X-fields with additional currents of the (V + A) type.

In Sec. 3 the minimal electromagnetic interaction of hadrons is considered, and in Sec. 4 their weak interaction, both as special cases of a unified primary isospin- and CP-invariant interaction, the symmetry of which is violated by one common cause: the mixing of vector bosons belonging to different isotopic multiplets.[6] A new approach to the understanding of the $|\Delta T| = 1/2$ rule and of its violation is proposed. It follows from the requirement that this rule be valid only "asymptotically" for $q^2 \gg M^2$, that for finite $q^2 \ll M^2$ the admixture of $|\Delta T| = 3/2$ is of the order $1/13$–$1/30$ in the amplitude, which is in satisfactory quantitative agreement with experiment.

The model also predicts a definite isotopic

*cf. also M. E. Mayer, Nuovo Cimento 11, 790 (1959), 17, 802 (1961) [Transl. note].

structure of the strangeness-conserving interactions ($\Delta S = 0$), for which in interactions with $\Delta T = 0, 1, 2$ for energies $E_{c.m.} \ll M$ the amplitudes are comparable to the ones in electromagnetic interactions. For $q^2 \gg M^2$, in the region where perturbation theory is still applicable, a direct computation in the $e^2$-approximation shows a clear tendency towards a restoration of the violated symmetry of the electromagnetic and weak interactions of the "bare" baryons.

The possibility of including the leptons into the scheme of violated isospin symmetry of the electromagnetic-weak interactions and the problem of higher $e^2$-approximations are not discussed.

## 2. THE SYMMETRIC "PRELIMINARY" LAGRANGIAN OF THE UNIFIED ELECTROMAGNETIC-WEAK INTERACTION OF HADRONS

We write down a relativistically invariant, isospin- and CP-invariant "preliminary" Lagrangian of the unified electromagnetic-weak interaction of the vector X-bosons with the hadron currents in the following form:

$$L_X = L_X^{(V-A)} + L_X^{(V+A)}, \quad (1)$$

where the first term contains the (V − A) current and the second term contains the (V + A) currents. The (V − A) Lagrangian is chosen according to [6, 7] in the form

$$L_X^{(V-A)} = 2^{-1/2} e [j^v X^v + j^s X^s + j^{Y(0)} X^{Y(0)} + f j^{u(0)} X^{u(0)}], \quad (2)$$

where e is the electric charge of the electron, $j^V$, $j^S$, $j^{Y(0)}$, and $j^{u(0)}$ are respectively the isovector, isospinor and isoscalar hadronic currents (the vector part of $j^{Y(0)}$ is the hypercharge current) having a (V − A) Lorentz-structure. For simplicity the vector index has been suppressed; the superscript (0) denotes neutral currents.

We shall consider that the currents $j^V$, $j^S$, and $j^{Y(0)}$ form a complete set of components of a unitary octet of currents. Under this assumption one can maintain for the present model all the practical results of the Cabibbo theory[8] without any additional assumptions.[7]

The isoscalar current $j^{u(0)}$ will be considered a unitary singlet.[1)] The X-bosons in (2) which are coupled to the (V − A) currents also form an octet and a singlet. The masses of all X-bosons will be considered equal to M. For the (V + A)-Lagrangian we write the following expression

$$L_X^{(V+A)} = 2^{-1/2} e [\tilde{j}^v \tilde{X}^v + \tilde{j}^{Y(0)} \tilde{X}^{Y(0)}], \quad (3)$$

where the $\tilde{j}$-currents have a (V + A) Lorentz structure, and as in (2) the upper indices denote their isospin properties. The masses of all $\tilde{X}$-bosons will be considered equal to $\tilde{M}$.

In the present model the sole cause of symmetry breaking (1) is the presence in the Lagrangian of the free "intermediate" vector fields of the two-particle interaction terms of the type of "non-diagonal mass," which will be written out below. These terms are due to the mixing of particles from different isospin multiplets and the displacement of their masses.

## 3. THE MINIMAL ELECTROMAGNETIC INTERACTION

For the sequel it is useful to make the following remark. It is easy to verify that a system of two boson fields $\varphi_1$ and $\varphi_2$ of equal mass m, coupled via the two-particle interaction

$$\Delta L = \mp \varkappa^2 \varphi_1 \varphi_2,$$

with $\kappa$ a constant to be called in the sequel "non-diagonal mass" or "mixing parameter," is equivalent to the following system of noninteracting $\psi$-fields

$$\psi_1 = 2^{-1/2}(\varphi_1 + \varphi_2), \quad \psi_2 = 2^{-1/2}(\varphi_1 - \varphi_2),$$

with the shifted masses

$$M_1^2 = m^2 \pm \varkappa^2, \; M_2^2 = m^2 \mp \varkappa^2, \quad \varkappa^2 \leqslant m^2.$$

If the fields $\varphi_1$ and $\varphi_2$ are components of different isospin multiplets, then the mixing produced by $\Delta L$ violates isospin symmetry. For $\kappa = 0$ one can achieve the indicated mixing of the fields $\varphi_1$ and $\varphi_2$, but since the $\psi$-fields have now coincident masses, the symmetry breaking is only apparent.

Let us mix the $X^{V(0)}$- and $X^{Y(0)}$-bosons in the Lagrangian (2) with vanishing nondiagonal mass $\kappa_1 = 0$, i.e., let us consider the fields

$$A_1 = 2^{-1/2}(X^{v(0)} + X^{Y(0)}), \quad A_2 = 2^{-1/2}(X^{v(0)} - X^{Y(0)}). \quad (4)$$

The masses of the $A_{1,2}$-fields are again equal to M. The mixing (4) leads to the following transformation of part of the Lagrangian (2)

$$j^{v(0)} X^{v(0)} + j^{Y(0)} X^{Y(0)} \to 2^{-1/2}(j^{v(0)} + j^{Y(0)}) A_1 + 2^{-1/2}(j^{v(0)} - j^{Y(0)}) A_2. \quad (5)$$

The vector part of the current $(j^{V(0)} + j^{Y(0)})$ has

[1)]The hypercharge current is the eighth component of a current octet only in the absence of supercharged particles [9]. In the sequel this will be assumed for the sake of simplicity, although for the model under consideration it is sufficient to consider $j^{Y(0)}$ as a hypercharge current, without specifying its SU(3)-properties. In the presence of supercharged particles, each of the isoscalar currents $j_v^{Y(0)}$ and $j_v^{u(0)}$ should be considered a superposition of a unitary octet and singlet.

an isospin structure identical to that of the electric current, and the current $(j^{V(0)} - j^{Y(0)})$ has the "complementary" isospin structure.

We carry out a similar mixing of the $\tilde{X}^{V(0)}$- and $\tilde{X}^{Y(0)}$-bosons in the Lagrangian (3) with a nonvanishing nondiagonal mass $\kappa_2^2 = \tilde{M}^2 - M^2$. The new fields

$$\tilde{A}_1 = 2^{-1/2}(\tilde{X}^{v(0)} + \tilde{X}^{Y(0)}), \quad \tilde{A}_2 = 2^{-1/2}(\tilde{X}^{v(0)} - \tilde{X}^{Y(0)}) \quad (6)$$

have the following masses

$$\tilde{M}_1^2 = M^2, \quad \tilde{M}_2^2 = 2\tilde{M}^2 - M^2. \quad (7)$$

The corresponding transformation of part of the Lagrangian (3) has the form

$$\tilde{j}^{v(0)}\tilde{X}^{v(0)} + \tilde{j}^{Y(0)}\tilde{X}^{Y(0)} \rightarrow 2^{-1/2}(\tilde{j}^{v(0)} + \tilde{j}^{Y(0)})\tilde{A}_1 + 2^{-1/2}(\tilde{j}^{v(0)} - \tilde{j}^{Y(0)})\tilde{A}_2. \quad (8)$$

The currents $(j^{V(0)} + j^{Y(0)})$ and $(\tilde{j}^{V(0)} + \tilde{j}^{Y(0)})$ differ from the electric current in their Lorentz $(V \mp A)$ structure.

In order to obtain a parity conserving minimal electromagnetic interaction it is sufficient to mix the $A_1$- and $\tilde{A}_1$-bosons with a mixing parameter $\kappa^2 = M^2$. The mixing gives rise to two new fields A and B

$$A = 2^{-1/2}(A_1 + \tilde{A}_1), \quad B = 2^{-1/2}(A_1 - \tilde{A}_1), \quad (9)$$

possessing the masses

$$M_A = 0, \quad M_B = \sqrt{2}M, \quad (10)$$

which interact respectively with vector and axial vector currents in a p- and C-conserving manner:

$$L_A = \frac{e}{2\sqrt{2}}(j^{v(0)} + j^{Y(0)} + \tilde{j}^{v(0)} + \tilde{j}^{Y(0)})A \equiv ej^{el}A, \quad (11)$$

$$L_B = \frac{e}{2\sqrt{2}}(j^{v(0)} + j^{Y(0)} - \tilde{j}^{v(0)} - \tilde{j}^{Y(0)})B \equiv ej^{b}B. \quad (12)$$

The current $j^{el}$ is identical with the electric current and the A-boson is identical with the photon. Therefore the interaction (11) is nothing else but the minimal electromagnetic interaction of the hadrons. The B-boson is a very heavy axial pseudophoton and the interaction (12) has the physical significance of an "isolated," weak, parity-conserving pseudoelectric interaction. In the present model this interaction is a faithful satellite of the usual electromagnetic interaction (11).

What are the possible experimental manifestations of the interaction (12)? In the Cabibbo theory[8] the neutral axial vector hadronic current differs in its charge structure from the electric current. However, the experimental effects of the current (12) in hadronic processes are, apparently, completely masked by the corresponding strong interactions. Therefore, if one does not consider the possibility of real generation of B-mesons, the experimental manifestations of the interaction (12) could hopefully be detected in principle in leptonic interactions. Indeed, due to the well-known universality of the electromagnetic interactions, the lepton terms can enter additively with the hadronic ones into the current $j^{el}$ in (11) and consequently into the current $j^{b}$ in (12). The considerations given above indicate that the charge structure of the axial vector leptonic current must be identical to the corresponding structure of the electric current of the leptons.

The presence of the interaction (12) among leptons should manifest itself, in particular, in violations of the angular correlations in electron-electron and electron-positron scattering, as predicted by quantum electrodynamics. These angular correlations are of the order of $\frac{1}{2}\alpha G$ and are very small for $q^2 \lesssim m_e^2$. For large 4-momentum transfers $q^2 \gg m_e^2$, if one discounts the possibility of real B-boson creation, the main manifestation of the interaction (12) is only some difference in the values of the "constant" of electromagnetic interactions of leptons in processes with real and virtual photons. The deviation of the differential cross section for e-e scattering from the prediction of usual quantum electrodynamics has the following expression in the center-of-mass system

$$\tfrac{1}{2}\alpha G_1 (4 / \sin^2\theta + 3)\, d\Omega. \quad (13)$$

For example, for $E_{c.m.} \sim 1$ GeV, the "anomalous" contribution to the e-e scattering cross section could reach ~0.2%. This effect could be verified experimentally in the near future in clashing electron-electron or electron-positron beams.

## 4. THE WEAK INTERACTIONS

The part of the Lagrangian (1) left over after separating off the interactions (11) and (12) refers to the domain of "weak" interactions. We shall construct the weak interactions of the hadrons according to the previously proposed scheme.[6] One has to repeat all the transformations carried out in [6] and make the following substitution in the final expression for the neutral currents and bosons:

$$X^{v(0)} \rightarrow A_2, \quad j^{v(0)} \rightarrow 2^{-1/2}(j^{v(0)} - j^{Y(0)}). \quad (14)$$

In addition one must explicitly take into account the additional term in (2) which is proportional to f.

For the sake of completeness we write out the fundamental formulas for the interactions of the charged currents also.[6] After mixing the charged isovector and isospinor bosons according to

$$\Delta L_1 = -k^2[X^{v(+)}X^{s(-)} + X^{v(-)}X^{s(+)}], \tag{15}$$

we obtain the following resulting expression for the Lagrangian of the semiweak interactions of the hadronic and leptonic[2)] currents:

$$L_W^{(\pm)} = \frac{1}{2}e[(l^{(+)} + j^{v(+)} + j^{s(+)})W^{(+)} + (l^{(+)} + j^{v(+)} - j^{s(+)})W'^{(+)} + \text{c.c.}], \tag{16}$$

where $l^{\pm}$ are the charged leptonic currents and the W-bosons are the symmetric combinations of the X-fields

$$W^{(\pm)} = 2^{-1/2}(X^{v(\pm)} + X^{s(\pm)}), \quad W'^{(\pm)} = 2^{-1/2}(X^{v(\pm)} - X^{s(\pm)}). \tag{17}$$

The masses of the charged W-bosons are

$$M_W{}^2 = M^2 + k^2, \quad M_{W'}{}^2 = M^2 - k^2. \tag{18}$$

In order to obtain agreement with the experimental data on the suppression of the strangeness-changing lepton-hadron processes, one must choose $\kappa \approx M/2$ (cf. [6]).

After mixing the neutral bosons according to

$$\Delta L_2 = -k_1{}^2(A_2X_1^{s(0)} + X^{u(0)}X_2^{s(0)}), \tag{19}$$

where $X_1^{S(0)}$ and $X_2^{S(0)}$ are the real and imaginary parts of the complex field $X^{S(0)}$, we obtain the following expression for the Lagrangian of the semiweak interactions of the neutral hadronic currents:

$$L_W^{(0)} = 2^{-3/2}e\{[j^{v(0)} - j^{Y(0)} - j^{s(0)} - j^{s(0)*}]W_1{}^{(0)} + [j^{v(0)} - j^{Y(0)} + j^{s(0)} + j^{s(0)*}]W_2{}^{(0)} + [-i(j^{s(0)} - j^{s(0)*}) + \sqrt{2}fj^{u(0)}]W_3{}^{(0)} + [i(j^{s(0)} - j^{s(0)*}) + \sqrt{2}fj^{u(0)}]W_4{}^{(0)}\}. \tag{20}$$

Here the $W_{1,2}^{(0)}$ bosons are, as in (17), the symmetric combinations of $A_2$ and $X_1^{S(0)}$, and the $W_{3,4}^{(0)}$ bosons are similar combinations of $X^{u(0)}$ and $X_2^{S(0)}$. The masses of the neutral bosons are

$$M_{1,3}^2 = M^2 + k_1{}^2, \quad M_{2,4}^2 = M^2 - k_1{}^2. \tag{21}$$

The corresponding resulting expression for the Lagrangian of the semiweak interactions of the $\tilde{j}$-currents has, according to (3) and (6), the following form

$$L_W{}^{(V+A)} = {}^1/_2\, e[\sqrt{2}(\tilde{l}^{(+)} + \tilde{j}^{v(+)})\tilde{X}^{v(+)} + (\tilde{j}^{v(0)} - \tilde{j}^{Y(0)})\tilde{A}_2 + \text{c.c.}], \tag{22}$$

where, as before, we have added the charged leptonic current $\tilde{l}^{(\pm)}$.

We write now the general expression for the electromagnetic-weak interactions of the hadrons in second order of e (the $e^2$-interaction), with virtual intermediate bosons. Making use of the expressions (16), (20), (22), and (11), (12), we find

$$\begin{aligned} L^{(e^2)} = {}^1/_4 e^2\{&[j^{v(+)}j^{v(-)} + j^{v(-)}j^{v(+)} + 2j^{s(+)}j^{s(-)}]\Delta_1(M^2, k^2, q^2) \\ &+ {}^1/_2[j^{Y(0)}j^{Y(0)} + j^{v(0)}j^{v(0)} + 4j^{s(0)}j^{s(0)*} \\ &- 2j^{v(0)}j^{Y(0)}]\Delta_1(M^2, k_1{}^2, q^2) + 2j^{v(-)}j^{s(+)}\Delta_2(M^2, k^2, q^2) \\ &- [j^{v(0)}j^{s(0)} - j^{Y(0)}j^{s(0)}]\Delta_2(M^2, k_1{}^2, q^2) \\ &+ f^2j^{u(0)}j^{u(0)}\Delta_1(M^2, k_1{}^2, q^2) - i\sqrt{2}fj^{u(0)}j^{s(0)}\Delta_2(M^2, k_1{}^2, q^2) \\ &+ 2[\tilde{j}^{v(+)}\tilde{j}^{v(-)} + \tilde{j}^{v(-)}\tilde{j}^{v(+)}]\Delta(\tilde{M}^2, q^2) \\ &+ [\tilde{j}^{Y(0)}\tilde{j}^{Y(0)} + \tilde{j}^{v(0)}\tilde{j}^{v(0)} - 2\tilde{j}^{v(0)}\tilde{j}^{Y(0)}]\Delta(2\tilde{M}^2 - M^2, q^2) \\ &+ 4j^{el}j^{el}\Delta(0, q^2) + 4j^bj^b\Delta(2M^2, q^2) + \text{c.c.}\}, \end{aligned} \tag{23}$$

where $\Delta(M^2, q^2)$ is the usual vector boson propagator for mass M and 4-momentum q, $\Delta(0, q^2)$ is the photon propagator, and $\Delta_1$ and $\Delta_2$ are the effective propagators introduced in [6]. They have the following explicit expressions

$$\Delta(M^2, q^2) = \frac{1}{M^2 + q^2}(\delta_{\alpha\beta} + q_\alpha q_\beta/M^2), \quad \Delta(0, q^2) = \delta_{\alpha\beta}/q^2, \tag{24}$$

$$\Delta_1(M^2, k^2, q^2) = \frac{2}{(M^2 + q^2)^2 - k^4}\left[(M^2 + q^2)\delta_{\alpha\beta} + q_\alpha q_\beta \frac{M^4 + k^4 + M^2q^2}{M^4 - k^4}\right], \tag{25}$$

$$\Delta_2(M^2, k^2, q^2) = -\frac{2k^2}{(M^2 + q^2)^2 - k^4}\left[\delta_{\alpha\beta} + q_\alpha q_\beta \frac{2M^2 + q^2}{M^4 - k^4}\right]. \tag{26}$$

In (23) $j^{el}$ is the electromagnetic current and $j^b$ is the neutral axial vector current. In all other cases the j-currents are (V – A)-currents and the $\tilde{j}$-currents are (V + A)-currents.

The following remark is important for the sequal. Considering four-fermion diagrams in the $e^2$-approximation of perturbation theory we find that the terms in the propagators (24)–(26) which are proportional to $q_\alpha q_\beta$ are proportional to the baryon masses $q_\alpha q_\beta \sim m_p^2$. One can neglect these terms if

$$q^2 \ll M^4/m_p{}^2 \approx (1000 \text{ GeV})^2. \tag{27}$$

The estimate (27) corresponds to the limit of ap-

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2)In the present model, as in [6], the leptons are not included in the scheme of broken isospin symmetry and the lepton interactions are described semiempirically. In (16) the charged leptonic currents are additively combined with the hadronic current $j^{v(\pm)}$. In agreement with indications from experiment, there should be no leptonic contribution to the neutral hadronic current $(j^{v(0)} - j^{Y(0)})$.

plicability of perturbation theory in a model with vector bosons, derived from unitarity in [10], $q^2 < (2000\ \text{GeV})^2$. Therefore, in the domain of applicability of perturbation theory (27), in the $e^2$-approximation one can neglect the terms with $q_\alpha q_\beta$ in all intermediate boson propagators in (24)–(26). This will be assumed in the following.

We consider the principal physical consequences of the Lagrangian (23).

1. The nonleptonic $|\Delta T| = 1/2$ rule and its violation. The Lagrangian (23) automatically satisfies the requirement $|\Delta s| < 2$, as in [6]. As regards the nonleptonic $|\Delta T| = 1/2$ rule, for $|\Delta S| = 1$, we have here a fundamental distinction. In the model of [6] the $|\Delta T| = 1/2$ rule was rigorous, valid for any momentum transfers $q^2$. It is easy to see that in the present model, owing to the substitution (14), this rule cannot be satisfied for all $q^2$. Indeed, making use of (23) and the Clebsch-Gordan coefficients one can see that the condition for rigorous $|\Delta T| = 1/2$ is

$$2^{-1/2}\Delta_2(M^2, k_1^2, q^2) = \Delta_2(M^2, k^2, q^2), \qquad (28)$$

which is impossible to realize for variable $q^2$.

Let us now introduce a new assumption. We require that the symmetry of the nonleptonic $|\Delta T| = 1/2$ rule be only "asymptotically" exact, for $q^2 \gg M^2$. Making use of (28) this requirement leads to the following relation (here the sum of $(|\Delta Y| = 1)$-violating interactions (15) and (19) behaves like an isospinor):

$$k_1^2 = \sqrt{2}k^2. \qquad (29)$$

For $q^2 \ll M^2$ the $|\Delta T| = 1/2$ rule is violated, there appear transitions with $|\Delta T| = 3/2$, with an amplitude for $q^2 = 0$ proportional to

$$2^{-1/2}\Delta_2(M^2, k_1^2, 0) - \Delta_2(M^2, k^2, 0) \approx 2k^2 / 13M^4, \qquad (30)$$

whereas the $|\Delta T| = 1/2$ amplitude is proportional to $2k^2/M^4$. A more precise calculation, taking into account the Clebsch-Gordan coefficients, shows that the relative suppression of the $|\Delta T| = 3/2$ transitions is characterized for various processes by a factor $(1/13 - 1/30)$ in amplitude, in satisfactory quantitative agreement with known experimental data. An additional reduction of the $|\Delta T| = 3/2$ amplitude for known processes at $q^2 \neq 0$ is insignificant due to the large mass proposed for the intermediate bosons assumed in this model.

It is easy to see that in the other extreme case of "asymptotic" domain of 4-momentum transfers $q^2 \gg M^2$ the following ratios for the amplitudes with transitions $|\Delta T| = 0,\ 1/2,\ 3/2$ are found:

$$A_0, A_{1/2}, A_{3/2} \sim q^{-2}, q^{-4}, q^{-8}. \qquad (31)$$

2. The suppression of the lepton-hadron strangeness changing processes. In distinction from the Cabibbo model, [8] the suppression of lepton-hadron strangeness changing processes, has in the present model a dynamical character and does not assume a suppression of the strangeness-changing hadronic current. A direct experimental verification of this point is possible in principle in high-energy antineutrino experiments (cf. [6]), but, unfortunately the assumed large mass of the intermediate bosons shifts this realization into the future.

3. Violation of CP-invariance. In the present model [11] the violation of CP-invariance is due to the $W_3^{(0)}$- and $W_4^{(0)}$-bosons in the Lagrangian (20). These bosons are coupled at the same time with the currents $j^{u(0)}$ and $(j^{s(0)} - j^{s(0)*})$, having different CP-parities

$$CPj^{u(0)} = +j^{u(0)}, \quad CPj^{s(0)} = +j^{s(0)*}.$$

In this sense the CP-violation is "localized" in distinction from the violation of space-parity. Comparison with experimental data on $K_2^0$-decay [12] leads to the estimate $f \approx 2 \times 10^{-3}$. Since by assumption the current $j^{u(0)}$ is an isoscalar, the $|\Delta T| = 1/2$ rule should be valid for nonleptonic CP-violating strangeness-changing processes, i.e., we should have

$$W(K_2{}^0 \to \pi^+ + \pi^-) \,/\, W(K_2{}^0 \to \pi^0 + \pi^0) = 2. \qquad (32)$$

It would be important to test this ratio experimentally.

The hypothesis that the CP-even neutral current contains also leptonic terms has been discussed in [11].

4. Parity nonconservation in nuclear forces. The odd p, (VA)-interference terms in the current products of (23) contribute to the nonleptonic space-parity-nonconserving $e^2$-interaction Lagrangian. Here the contributions from the jj-terms and from the $\tilde{j}\tilde{j}$-terms have opposite signs. Making use of (23)–(26) one can see by direct calculation that the following conclusions hold: (a) for small $q^2 \ll M^2$ the odd-P isospin-changing transition amplitudes (with $|\Delta T| = 0, 1, 2$) have approximately the ratios $1 : 1/2 : 1/4$ (for $\tilde{M} \neq M$), i.e., are of the same order; (b) in the "asymptotic" region $q^2 \gg \tilde{M}^2$ the following ratios among amplitudes hold

$$A_0, A_1, A_2 \sim q^{-2}, q^{-4}, q^{-6}. \qquad (33)$$

The physical effects of parity nonconservation in nuclear interactions will drastically depart from these estimates for the following reason. The principal contribution to parity-nonconserving nuclear forces with $\Delta T = 0$ leads to interference of the above-mentioned odd-P amplitude of weak interactions with the corresponding strong interaction amplitude; the interference term is proportional to the Fermi constant G. Owing to isotopic invariance of the strong interactions, however, the main contribution to the strangeness nonconserving nuclear interactions with isospin change $|\Delta T| = 1, 2$ leads only to an interference of the odd-P amplitude of weak interactions with the corresponding P-even amplitude of the electromagnetic interactions; this term is proportional to $\alpha G$. In principle the experimental verification of these conclusions is possible, although very complicated.

5. The isospin noninvariant nuclear forces. In addition to the strangeness-changing and odd-P interactions, the $e^2$-Lagrangian (23) also describes even-P $\Delta S = 0$ interactions. By assumption, these latter contain all isospin-noninvariant nuclear forces, including the electromagnetic ones, since the "strong" interactions not taken into account in (23) are considered to be rigorously isospin-invariant. The part of the Lagrangian which is responsible for the indicated interactions contains (VV) and (AA) terms coming from products of currents (products of two vector- or two axial-vector currents). Therefore, in distinction from the previous case, the jj-terms and the $\tilde{j}\tilde{j}$-terms contribute with equal signs, in addition to the contributions of the electromagnetic (VV-term) and B-interaction (the AA-term).

As before, a direct computation shows the truth of the following conclusions: a) for $q^2 \ll M^2$ the even-P amplitudes of the transitions with $|\Delta T| = 0, 1, 2$ practically coincide with the corresponding electromagnetic amplitudes and are of comparable magnitude; b) in the asymptotic region $q^2 \gg \tilde{M}^2$ the following relations are verified among the even-P amplitudes for transitions with $|\Delta T| = 0, 1, 2$:

$$A_0, A_1, A_2 \sim q^{-2}, q^{-4}, \quad \{q^{-4}[(VV) - (AA)] + O(1/q^6)\}. \tag{34}$$

Here [(VV) − (AA)] denotes the difference of the two isotensors (T = 2) which appear respectively in the decomposition of products of vector and axial vector isovector currents. One should note that in deriving the result (34) it was essential that "electromagnetic" interactions, "B-interactions" and "weak interactions" from the unified Lagrangian (23) give comparable contributions, since for $q^2 \gg \tilde{M}^2$ the latter become as strong as the electromagnetic interactions, and the amplitudes differ from that of the electromagnetic interaction only by terms of higher order in $1/q^2$.

It is interesting to note that under the condition (34) the weak interactions lead in the present model to a cut-off of the divergences of the electromagnetic mass differences within isotopic multiplets for large momenta of the virtual particles.

6. The case of absence of charged leptonic (V + A)-currents. The most economic version of the model of electromagnetic-weak interaction of the type under discussion, not containing any free parameters, corresponds to the choice $M \equiv \tilde{M}$. The formulation of the theory is simplified in this case, since $\kappa_1 = \kappa_2 = 0$. One can avoid contradictions with the known experimental data on weak interactions only in the absence of charged leptonic (V + A)-currents. The nonconservation of spatial parity in nonleptonic processes is in this case completely accounted for by the presence of the S-currents in the Lagrangian (2).

We note that the absence of charged leptonic (V + A)-currents is a direct consequence of the two-neutrino theory of weak interactions, with one leptonic charge and strict $\gamma_5$-symmetry of the massive leptons[13, 14] or, alternatively of a theory with two leptonic charges. It is interesting that the lepton terms can combine into a neutral (V + A)-current and the proposed "mechanism" for obtaining parity conservation in electromagnetic interactions is in principle applicable to the leptonic terms, too.

7. The case of presence of charged leptonic (V + A) currents. Parity conservation in the electromagnetic interactions of hadrons has been obtained above at the cost of introducing hadronic currents of the (V + A) type. Since the leptons participate in the electromagnetic and in the known weak interactions, one could expect that there exist also charged leptonic (V + A) currents, entering additively into the $\tilde{j}^{V(\pm)}$-currents of the Lagrangian (3) with the same universal constant. Such a possibility exists only in a theory with two neutrinos and a single leptonic charge,[13] which suggests the following concrete form for these currents:

$$\tilde{j}_l^{(\pm)} = (\bar{e}\gamma_\alpha(1-\gamma_5)\tilde{\nu}_\mu) + (\bar{\mu}\gamma_\alpha(1-\gamma_5)\tilde{\nu}_e). \tag{35}$$

It follows that in weak processes determined by the (V + A) currents anomalous lepton pairs $(\bar{\nu}_\mu, e^-)$ and $(\bar{\nu}_e, \mu^-)$ should be observed in addition to the normal pairs $(\nu_e, e^-)$ and $(\nu_\mu, \mu^-)$.[3)] Such

[3)]A characteristic possibility of the two-neutrino- one-leptonic-charge hypothesis is the possibility of "neutrino flip" of the type $(\nu_e \leftrightarrow \mu^+)$, $(\nu_\mu \leftrightarrow e^+)$. It is possible that the assumption of strict $\gamma_5$-symmetry of the massive leptons in weak interactions may be too restrictive [14] and should be replaced by the assumption of (V − A) dominance, suggested by experiment.

"neutrino-flip" phenomena could, in principle, be observed in beta decay, in muon decay, in high-energy neutrino experiments and others.

The additions to the Lagrangians for beta and muon decays due to the $\tilde{j}$-currents are of the form

$$\Delta L_\beta \sim \left(\frac{M}{\tilde{M}}\right)^2 \frac{G}{\sqrt{2}} (\bar{p}\gamma_\alpha (1-\gamma_5) n) (\bar{e}\gamma_\alpha (1-\gamma_5) \tilde{\nu}_\mu), \quad (36)$$

$$\Delta L_\mu \sim \left(\frac{M}{\tilde{M}}\right)^2 \frac{G}{\sqrt{2}} (\bar{\tilde{\nu}}_e\gamma_\alpha (1-\gamma_5) \mu) (\bar{e}\gamma_\alpha (1-\gamma_5) \tilde{\nu}_\mu)$$
$$= -\sqrt{2}\left(\frac{M}{\tilde{M}}\right)^2 \frac{G}{\sqrt{2}} (\bar{\nu}_\mu (1-\gamma_5) \mu) (\bar{e} (1+\gamma_5) \nu_e). \quad (37)$$

Admixtures of the interactions (36) and (37) should lead to deviations of the asymmetries and longitudinal polarizations in these decays from the predictions of the usual (V – A) theory.[14] In high-energy neutrino experiments the muon neutrinos should generate positrons. The accuracy of experimental data on these phenomena, attained to date is of the order of 1%.[15-17] It does not exclude an admixture of 10% (V + A)-coupling in the Lagrangian and allows only to conclude that $\tilde{M} \gtrsim 3M$. Further increase in accuracy of the experimental data is extremely desirable.

## 5. DISCUSSION AND CONCLUSIONS

1. In the proposed model of unified electromagnetic-weak interactions of the hadrons the conservation of the strangeness-conserving weak vector current is automatically satisfied,[18] since the isotopic relatedness of the electric hadron current and this weak current is explicitly included. We note that in distinction from the Cabibbo model,[8] no quantity of the type cos $\theta$ appears here, in violation of the initially assumed equality of the vector coupling constant for beta decay and the "bare" weak interaction constant. In fact, the existence of a conserved vector current is in itself an important argument in favor of a unified electromagnetic-weak interaction.

2. In the present paper the Lagrangian of the electromagnetic-weak interaction is investigated in detail for hadrons, in the $e^2$-approximation. Only in this approximation all violation of the initial isospin symmetry of the electromagnetic-weak interaction of hadrons is completely determined by the explicitly given non-diagonal mass terms for the vector bosons. In higher approximations than $e^2$, the isospin symmetry violation will be determined also by virtual leptons, and without making additional explicit definitions of the violated isotopic properties of the leptons it is impossible to draw further conclusions.[4)] One may hope, however, that the fundamental results derived in the $e^2$-approximation in the domain of applicability of perturbation theory ($q^2 < (1000 \text{ GeV})^2$) will, to some extent, remain meaningful in the exact theory also. In particular, one might hope that in the exact theory the "hierarchy of symmetries" rule derived above will survive in the asymptotic region $q^2 \gg \tilde{M}^2$.

We remark that, although the quantity M has a well-defined meaning in the model under discussion, ($M \sim 30\ m_p$), the quantity $\tilde{M}$ is a free parameter, which has to be determined from experiment, for instance from the magnitude of the violation of (V – A) coupling in beta-decay, in muon decay, or in high-energy neutrino experiments. From the experimental data known at present for these processes, one can only conclude that $\tilde{M}^2 > 10M^2$, whereas the applicability of perturbation theory in the "asymptotic region" is determined by the condition $\tilde{M}^2 \ll 1000M^2$. On the other hand, as has been shown, there exists a "most economical" version (for the present time) of the unified electromagnetic-weak interaction model for hadrons, in which $\tilde{M} \equiv M$ and the applicability of perturbation theory is guaranteed in the asymptotic region.

3. We have introduced above the assumption that the symmetry of the nonleptonic $|\Delta T| = 1/2$ rule is exact only "asymptotically," for $q^2 \gg M^2$. In the model under consideration this assumption leads to the relation (29), according to which the violation of the $|\Delta T| = 1/2$ rule for small $q^2 \approx 0$ is determined by an admixture of $|\Delta T| = 3/2$ transitions which are weaker in amplitude 13–30 times, whereas for large momentum transfer $q^2 \gg M^2$ the amplitudes for $|\Delta T| = 1/2$ and $|\Delta T| = 3/2$ transitions are respectively of order $q^{-4}$ and $q^{-8}$.

In addition, it turns out, that a rule analogous to the "hierarchy of symmetries" rule is automatically fulfilled in the region of momentum transfers $q^2 \gg \tilde{M}^2$ for the amplitudes of all other types of electromagnetic-weak transitions described by the $e^2$-Lagrangian (23). This is true in particular for the odd-P and even-P strangeness-conserving transitions. In both latter cases the isospin-changing amplitudes with $|\Delta T| = 0, 1, 2$ are respectively of the orders $q^{-2}$, $q^{-4}$, $q^{-6}$.[5)] This suggests another way of understanding the nonleptonic $|\Delta T| = 1/2$ rule and its violation.

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4)In addition, in higher approximations the fundamental difficulties with divergences crop up, the importance of which will also not be discussed here.

5)There is a singularity for the even-P, T = 2 amplitude, cf. (34).

If the "symmetry-hierarchy" rule (i.e., the rule that in the asymptotic region of large momentum transfers $q^2 \gg M^2$ the amplitudes for transitions with larger changes of internal quantum numbers are of higher order of smallness than the amplitudes with smaller variations of the quantum numbers) is taken as one of the starting points of the model, then, since $|\Delta T| = 1/2$ is the minimally possible variation of isospin for a transition with $|\Delta S| = 1$, the "symmetry-hierarchy" rule implies the relation (29). Consequently the $|\Delta T| = 1/2$ rule and its violation appear as one of the consequences of the "hierarchy" rule and of the (current) × (current) form of the interaction in the $e^2$-approximation of perturbation theory. The suppression of the $|\Delta T| = 3/2$ amplitude for $q^2 \approx 0$ is a specific consequence of the present model which agrees with experiment. For other transitions (with $\Delta S = 0$) such a suppression does not occur (cf. supra).

We note that the conclusion about the existence of a tendency to restore the violated isotopic symmetry in the domain of applicability of perturbation theory is independent of the choice of the parameters of the model and is automatically fulfilled. But the "hierarchy" rule requires more. One can, it seems, consider the postulated absence of $\Delta S = 2$ transitions as another consequence of the "hierarchy" rule.

Since, by assumption, only the electromagnetic and weak interactions of the hadrons are isospin-noninvariant, and these have been taken into account by the present model, the indicated restoration of isospin symmetry of the ensemble of hadronic interactions in the limit of large 4-momentum transfers, as well as the "hierarchy" rule, are in principle observable effects, which in the future could be subjected to experimental verification.

4. Owing to the large number of intermediate bosons (the present model contains thirteen!) the proposed formulation is extremely uneconomical. However this impression does not reflect the essence of the situation, since the number of mass parameters for the intermediate bosons is minimal (one or two mass values), and the various bosons could be considered as different states (isospin, unitary, etc.) induced by the postulated new symmetry of the electromagnetic-weak interactions (i.e., states of one or two kinds of intermediate fields). In this connection it is interesting to note that the history of theoretical physics suggests examples in which an increase in symmetry was related to a growth of the number of fundamental states of particles (or fields).

5. The only justification for the inclusion of (V + A)-currents in the present model was the necessity of deriving parity conservation in electromagnetism, starting from a parity-nonconserving unified isospin-invariant "preliminary" Lagrangian. For this purpose it was sufficient to choose approximately half as many (V + A)-currents as (V − A)-currents. It is however possible, from the point of view of the higher symmetry, to require that the "preliminary" Lagrangian possess a broken (V ± A) symmetry and that the system of (V + A)-currents include also the unitary octet and singlet. In this case the complete set of currents-generators of the possible strong interaction symmetry group SU(3) × SU(3)[19] would participate in the unified electromagnetic-weak interactions.

6. The present model includes a set of parameters (boson masses and mixing parameters) which have to be determined from experiment. The model proves the possibility of such a formulation, but not its necessity. An obvious deficiency of such a formulation is the absence of theoretical arguments for the selection of the numerical values of a series of fundamental constants. It would be desirable that a physical quantity like the vanishing photon mass should be a necessary consequence of the theory. In a series of places the formulation given is not unique and could be perfected.

But the main purpose of the proposed model was to exhibit the possibility of formulating a unified electromagnetic-weak interaction of hadrons, possessing broken isospin symmetry and which is compatible with all presently known experimental data. An experimental verification of the fundamental ideas which are realized in this model would be of decisive importance. In particular, the experimental detection of a small admixture of (V + A) currents in the known weak interactions, or the discovery of the B-interaction could be an important argument in favor of a unified description of electromagnetic and weak interactions.

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Note added in proof (April 3, 1966) 1. It is easy to see that the estimate of the relative suppression of the $|\Delta T| = 3/2$ amplitude given in the text, will not be considerably changed by making use of the exact propagators of the intermediate bosons (26) for arbitrary $q_\alpha q_\beta$, and therefore remains valid if one considers virtual strong interactions up to any order.

2. The realization of the indicated possible restoration of broken isospin symmetry of the unified electromagnetic-weak interaction in the limit of large momentum transfers is in the general case ("switching" of virtual strong interactions) closely related to the following two assumptions: 1) in the

limits all weak currents are conserved $q_\alpha j_\alpha < C/|q|$; 2) in the diagrams which violate the current-current form of the Lagrangrian (23), involving virtual hadrons, the large invariant squared momentum transfer is associated preferentially with the W-boson.


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