Electric dipole moment of the neutron in gauge theory

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One of the consequences of violation of *CP* invariance of the physical world is the existence of an electric dipole moment of elementary particles. The renormalization gauge theory of the electroweak and strong interactions developed during the past decade has revealed several possible sources of violation of *CP* invariance: direct violation of *CP* invariance in the Lagrangian of the electroweak interactions, spontaneous violation of *CP* invariance, and violation of *CP* invariance in the strong interactions described by quantum chromodynamics. The present review is devoted to a discussion of the predictions for the electric dipole moment of the neutron which follow from the various sources of violation of *CP* invariance in the theory. It includes the theoretical results obtained in the framework of gauge theory during the past decade up to the beginning of 1982. A comparison of the prediction of various gauge models with the experimental measurements of the electric dipole moment will make it possible to gain a better understanding of the nature of violation of *CP* invariance.

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CONTENTS

1. INTRODUCTION: HISTORY OF THE PROBLEM AND MECHANISMS OF VIOLATION OF *CP* INVARIANCE IN GAUGE THEORY

The history of the problem concerning the existence of an electric dipole moment of elementary particles goes back to the work of Purcell and Ramsey.[1] At that time, it was assumed that the physical world is invariant with respect to spatial reflection—P inversion. Since the electric dipole moment is a polar vector,

$$\mathbf{D} = \int \mathbf{r}\rho(\mathbf{r})\, d^3r,$$

where ρ is the distribution of charge density, and an elementary particle has no orientation other than the spin—an axial vector, the existence of an electric dipole moment meant a violation of P invariance, and Purcell and Ramsey had to resort to a rather unconvincing scheme for the construction of a P-even electric dipole moment from magnetic charges and orbital angular momentum. However, they performed the service of drawing attention to the need to measure the electric dipole moment as a physical characteristic of particles and establishing, using the data of certain experiments, the first limits on the electric dipole moment of the neutron:

$$D_n = |\mathbf{D}_n| \leqslant 10^{-13} - 3\cdot 10^{-18}\ e\cdot\text{cm}.$$

When in 1956–1957 it was discovered that P invariance is not a strict law of nature,[2,3] particular activity in the study of electric dipole moments did not develop, since the idea of invariance of the physical world with respect to the combined CP inversion, which was formulated during the same period, forbade, as before, by virtue of the CPT theorem, an electric dipole moment as a quantity which is not only P-noninvariant but also T-noninvariant.[4] Therefore widespread interest in the theoretical and experimental investigation of electric dipole moments arose only after the discovery of CP violation in K_L decays in 1964.[5]

Various methods have been invoked for the experimental investigation of the electric dipole moments of elementary particles, and their description can be found, for example, in the review of Shapiro.[6] So far, only upper limits on the electric dipole moments of elementary particles have been obtained. If we represent the amplitude for interaction of the dipole moment of a fermion with the potential A_μ of the electromagnetic field in the form

$$if_D(k^2)\,\bar{\psi}\left(p+\frac{k}{2}\right)\sigma_{\mu\nu}k_\nu\gamma_5\psi\left(p-\frac{k}{2}\right)A_\mu(k), \tag{1}$$

the dipole moment is

$$D \equiv f_D(0), \tag{2}$$

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and for the muon, electron, proton, Λ hyperon, and neutron we have the following limits:

$$D_\mu \leqslant (0.8 \pm 4.3)\cdot 10^{-19}\ e\cdot\text{cm}^{7},$$
$$D_e \leqslant 3\cdot 10^{-24}\ e\cdot\text{cm}^{8},$$
$$D_p \leqslant 2\cdot 10^{-20}\ e\cdot\text{cm}^{9},$$
$$D_\Lambda = (-3.0 \pm 7.4)\cdot 10^{-17}\ e\cdot\text{cm}^{10},$$
$$D_n < 6\cdot 10^{-25}\ e\cdot\text{cm}^{11}.$$

Of all the baryons, the neutron is the most convenient object for precision measurements of the electric dipole moment, owing to the vanishing of its electric charge, its sufficient stability, and the possibility of using beams of ultracold particles.

However, the very observation of an electric dipole moment might be a second experiment in which one could see a violation of CP invariance. So far, apart from the decays of strange particles (K mesons), no such violation has been observed, and an independent measurement of the parameters of violation of CP invariance in a strangeness-conserving process might make it possible to ascertain the mechanism of violation of CP invariance.

Since the experimental discovery of nonconservation of CP invariance many diverse mechanisms of violation of CP invariance have been proposed and a large number of estimates of the electric dipole moments of particles have been obtained. The reader can find references to earlier studies in the paper of Dress *et al.*[12] In the present review, we shall consider the results of calculation of the electric dipole moments of the neutron and other particles in the framework of the renormalizable gauge theory of the weak, electromagnetic, and strong interactions which has been developed in the past decade.

In a gauge-invariant theory, there exist three sources of violation of CP invariance.

1. The first source relates to the possibility of a difference between the phase factors of the constants for coupling of the gauge fields to the individual weak currents, and it realizes the possibility of direct violation of CP invariance in the initial Lagrangian. A phase displacement is possible both between left-helicity and right-helicity currents[13-17] and between left-helicity currents alone.[18] As long as the theory contained four types of quarks (u, d, s, c), both left- and right-helicity currents were required for the introduction of CP noninvariance. But if the theory includes six types of quarks (u, d, s, c, b, t), then CP violation can already occur on the basis of left-helicity currents alone. Since five types of quarks (u, d, s, c, b) have now been discovered and the experimental data favor the $SU(2)_L \otimes U(1)$ model, in which the left-helicity quarks are grouped into doublets, the existence of the t quark seems highly probable and even necessary on the basis of arguments concerning the compensation of the triangle anomalies[68] if we bear in mind that the leptons are grouped into the three left-helicity doublets

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L.$$

Then the hadronic sector includes the three quark doublets

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b \end{pmatrix}_L,$$

and this is sufficient for the operation of the simple mechanism of violation of CP invariance indicated by Kobayashi and Maskawa.[18]

The virtues of the 6-quark $SU(2)\otimes U(1)$ model, namely, its ability to provide a correct description of the electroweak interactions with the simplest structure of the Lagrangian and the minimum number of Higgs fields (a single physical scalar field is sufficient), compel us to pay particular attention to the analysis of the electric dipole moment of the neutron in this scheme. The results are presented in Sec. 2.

Although the conclusion about the extremely small dipole moment $D_n \sim 10^{-32}\ e\cdot\text{cm}$ may discourage the experimentalists, it is important for ascertaining the true mechanism of CP violation, since other schemes of violation of CP invariance, which are considered in Secs. 3 and 4, generally give much larger values $D_n \sim 10^{-23}$–$10^{-30}\ e\cdot\text{cm}$. However, these schemes are inferior from an esthetic point of view, since they require an extension of the Higgs sector of the theory. Moreover, some of them include a mechanism of spontaneous violation of CP invariance which should lead to a splitting of the Universe into domains,[83] which is not confirmed by observational data.

2. The second source of CP noninvariance relates to the possibility of spontaneous CP violation in the Higgs-field sector. The first to draw attention to this was T. D. Lee,[19,20] and his idea was subsequently developed in Refs. 21–23 and in a different formulation, without interactions of quark-flavor-changing neutral currents, was investigated by Weinberg[24] and others.[25-28]

In the case of spontaneous CP violation, the initial Lagrangian has a CP-invariant form and CP violation occurs because the Higgs field is chosen to be a certain particular solution which does not possess in full measure the symmetry properties of the Lagrangian. This mechanism is due to the presence in the theory of a so-called condensate, i.e., nonzero vacuum expectation values of the Higgs fields, and in the variant of Refs. 19–21 it requires the existence of at least two multiplets of Higgs fields, and in the variant of Ref. 24 at least three Higgs multiplets, whose vacuum expectation values have different phases.

As we have already noted, in spontaneous-violation models there is a difficulty associated with the absence of a domain structure of space. Nevertheless, the mechanism of spontaneous CP violation has been widely discussed in the literature. In Sec. 3 of this review we consider the predictions which follow for the electric dipole moment of the neutron in Weinberg's model of CP violation.[24] This model is closest to the standard schemes for construction of a gauge theory, as it contains the usual GIM mechanism[31] of compensation of the quark-flavor-changing neutral currents. Other models of CP violation are considered in Sec. 4. Some of them simultaneously contain the mechanisms of direct and spontaneous CP violation.

3. The third source of CP violation related to the properties of the strong-interaction theory described by quantum chromodynamics (QCD). The nontrivial structure of the vacuum in QCD and the existence of instanton solutions,[53] which convert one vacuum into another with different topological charges, make it necessary to add to the Lagrangian a so-called θ term,[54] which is odd with respect to the CP transformation.

For $\theta \sim 1$, there should in general be a strong violation of CP invariance. The experimental absence of an appreciable CP violation means that the parameter θ is either extremely small or simply equal to zero. The conclusion that the parameter θ is extremely small ($\theta < 10^{-9}$) results from a comparison of the estimates of the electric dipole moment of the neutron

$$D_n \sim 10^{-16} \mid \theta \mid e \cdot \mathrm{cm},$$

obtained in Refs. 62, 65, and 66, with the experimental data.

The experimental limit on θ compels us to modify the theory in such a way that the effective value of the parameter θ is less than 10^{-9} or equal to zero. One of the ways of achieving this is to require an additional global U(1) symmetry of the Lagrangian,[57] which can be realized if either the mass of at least one quark is equal to zero[57] or the Higgs sector of the theory is enlarged. In the latter case, there appears in the theory a light pseudoscalar particle—an axion.[58,59]

While the requirement of a vanishing quark mass encounters theoretical objections,[60] recent investigations have shown that the realization of U(1) symmetry as a result of an enlargement of the Higgs sector can be accomplished in such a way that the axion which occurs is practically unobservable. This solves the problem of the experimental absence of axions,[61] and the vanishing of the effective value of the parameter θ solves the problem of the large values of the electric dipole moment in quantum chromodynamics. The situation is elucidated in greater detail in Sec. 5.

2. ELECTRIC DIPOLE MOMENT OF THE NEUTRON IN THE KOBAYASHI-MASKAWA MODEL

a) Parametrization of the theory and result of the two-loop approximation

The introduction of CP violation in a gauge-invariant theory is by no means a simple problem. In particular, in the original four-quark variant of the $SU(2)_L \otimes U(1)$ model of the electroweak interactions[29] CP violation was impossible. In 1973 there appeared a paper by Kobayashi and Maskawa,[18] who noted that in the presence of three or more doublets of left-helicity quarks CP violation can occur as a result of complex constants for the interaction of the individual charged left-helicity currents with the intermediate vector bosons. The Higgs sector of the theory is then taken to be CP-invariant.

In a scheme with N left-helicity doublets the complete set of charged left-helicity currents can be represented in the form

$$\bar{q}^k_{\mathrm{up}} \gamma_\mu (1 + \gamma_5) U^{kl} q^l_{\mathrm{down}},$$

where q^k_{up} are the upper and q^l_{down} are the lower components of the doublets, and $k, l = 1, 2, \ldots, N$.

The $N \times N$ unitary matrix U, which describes rotations in the space of quark flavors, contains N^2 parameters, $(2N-1)$ of which can be eliminated by a redefinition of the phases of the quark fields, while $(N-1)^2$ remain as physical parameters. Of these, $N(N-1)/2$ are real and $(N-1)(N-2)/2$ are complex. Thus, it is only beginning with $N=3$ that it becomes possible to introduce into the theory constants whose complex character could lead to physical phenomena.

Such phenomena include CP violation. Indeed, the properties of the amplitude A for some process with respect to CP inversion are established by comparing $(CP)A$ and A^+. But CP inversion does not include complex conjugation of the constants, while Hermitian conjugation does; consequently, the individual terms proportional to the imaginary and the real part of the overall coefficient possess different properties with respect to CP inversion, and this is interpreted as a violation of CP invariance.

The left-helicity quark doublets of the six-quark $SU(2)_L \otimes U_1$-symmetric gauge model of the electroweak interactions can be chosen in the form

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b_\theta \end{pmatrix}_L, \tag{3}$$

where d_θ, b_θ, and s_θ are the linear superpositions of the d, s, and b quarks defined by the equations

$$\begin{aligned} d_\theta &= dc_1 - (sc_3 + bs_3) s_1, \\ s_\theta &= [ds_1 + (sc_3 + bs_3) c_1] c_2 - (ss_3 - bc_3) s_2 e^{i\delta}, \\ b_\theta &= [ds_1 + (sc_3 + bs_3) c_1] s_2 + (ss_3 - bc_3) c_2 e^{i\delta}, \end{aligned} \tag{4}$$

in which $c_i \equiv \cos\theta_i$, $s_i \equiv \sin\theta_i$, and θ_i are mixing angles analogous to the Cabibbo angle in the four-quark variant of the theory.

It is easy to see that the $SU(2)_L \otimes U(1)$-symmetric scheme includes the usual GIM mechanism[31] of compensation of the quark-flavor-changing neutral currents.

In application to quark-flavor-changing transitions, in particular to decays of K_L mesons, the phase mechanism makes it possible to obtain values of the phenomenological CP-violation parameters ε, ε', and Φ_D in agreement with experiment (Refs. 32, 47, 77, 78, 80, and 81).

In relation to the diagonal transitions, it appears that by virtue of the non-self-adjointness of an amplitude which includes a chain of transitions, for example,

$$(\bar{u}d)(\bar{d}c)(\bar{c}s)(\bar{s}u) \tag{5}$$

(and the non-self-adjointness is a consequence of the different s phases in the currents $\bar{c}s$ and $\bar{u}s$), such transitions should exhibit observable CP-odd effects.

Therefore the original estimates[32-34] of the electric dipole moment were based on a calculation of a certain (incomplete) set of diagrams of the type shown in Fig. 1 and led to an electric dipole moment of the quark of order

$$D_{u,d} \sim m_{u,d} \frac{eG_F^2 m_q^4}{(2\pi)^4 M_W^2}. \tag{6}$$

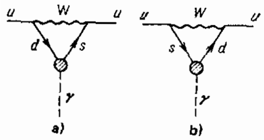

FIG. 1.

Since the electric dipole moment of a baryon is a static characteristic, and the experience of calculating another static characteristic—the magnetic moment—teaches us that the model of composition of the total static moment from the moments of the individual quarks leads to good agreement with experiment,[35] it also seems natural to form the electric dipole moment of a baryon by combining the electric dipole moments of the individual constituent quarks. Then for the electric dipole moment of the neutron it is natural to expect estimates of the same order of magnitude as for the electric dipole moment of a constituent quark.

However, further investigations showed[36] that the result (6) cannot be used. The point is that although the individual diagrams give contributions of the order (6) to the electric dipole moment of a quark, the summation of all the two-loop diagrams leads to the result $D = 0$. It is easy to see this by taking into account the fact that the contribution to the electric dipole moment of the u quark, for example, is determined by the difference between the diagrams of Figs. 1a and 1b and by using the expression for the ds γ vertex obtained in Ref. 37,

$$\Gamma_\mu^{\bar{d}s\gamma} = -\frac{2cQ_u}{M_W^4}\left(\hat{p} - \frac{\hat{k}}{2} - m_d\right)\gamma_\mu(1-\gamma_5)\left(\hat{p} + \frac{\hat{k}}{2} - m_s\right) + \frac{c(Q_u - 3Q_d)}{2M_W^4} i\varepsilon_{\mu\sigma\tau\eta} k_\sigma p_\tau \gamma_\eta (1+\gamma_5) + O(k^2), \tag{7}$$

where Q_u and Q_d are the charges of the u and d quarks, and $c = ic_2 s_1 s_2 s_3 (4\pi)^{-2}(m_c^2 - m_t^2)$. The formula for $\Gamma_\mu^{\bar{s}d\gamma}$ is obtained from the preceding one by the interchange of m_d and m_s.

On substitution of $\Gamma_\mu^{\bar{d}s\gamma}$ and $\Gamma_\mu^{\bar{s}d\gamma}$ into the amplitudes corresponding to the diagrams of Figs. 1a and 1b, their difference is equal to zero, apart from terms of first order in k, so that in the two-loop approximation

$$f_D(0)\,|_{g^4} = 0. \tag{8}$$

Therefore further investigations of the electric dipole moment of a baryon were made in two directions: first, a study was made of the influence of radiative corrections on the magnitude of the electric dipole moment of a quark, and second, an estimate was made of the possible contribution to the electric dipole moment of a baryon from interquark exchange forces.

b) Electric dipole moment of the quark with allowance for gluon loops

In the calculation of the contribution to $f_D(k^2)$ from the diagrams of Fig. 1, we were able to note that the result (8) was based essentially on the fact that the d and s quarks propagated under identical conditions, i.e., their interactions with the other fields were symmetric. Therefore a nonzero value of f_D might be obtained, for example; in a situation in which the conditions of propagation of the d and s quarks are different. Such a situation is represented by the diagrams of Fig. 2, in which the broken lines denote gluons.

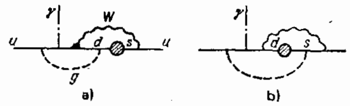

FIG. 2.

If the resulting electric dipole moment is estimated by using, for example, only the diagram of Fig. 2a, one can easily reach the erroneous conclusion that the gluon corrections play an exceptionally important role. In particular, the amplitude corresponding to the diagram of Fig. 2a contains terms of order

$$m_u \frac{\alpha_s}{\pi} \frac{eG_F^2}{(2\pi)^4} m_q^2, \tag{9}$$

which are M_W^2/m_q^2 times larger than the contributions (6) to the electric dipole moment of the quark from the individual two-loop diagrams. But there is a mutual cancellation in the sum of the contributions of the individual two-loop diagrams. What happens to the three-loop diagrams? In the literature, one can find the claim that Eq. (9) actually determines the magnitude of the electric dipole moment of the quark[38a] in the class of three-loop diagrams, while in the class of four-loop diagrams[38] we have

$$D_u \sim m_u \left(\frac{\alpha_s}{\pi}\right)^2 \frac{eG_F^2}{(2\pi)^4} m_q^2. \tag{10}$$

However, a detailed investigation of the problem showed that in the class of three-loop diagrams there is a mutual cancellation of the large terms (9) when certain types of diagrams are summed.[39] Thus, the sum of the amplitudes corresponding to the diagrams of Figs. 2a and 2b no longer contains terms of the order (9).

In the three-loop approximation, even in a simplified case, it is necessary to consider a total of 54 diagrams. Each of them corresponds to an amplitude containing several terms with different γ-matrix structures. Therefore it is difficult to investigate the exact value of D in the three-loop approximation, but it can be shown that on the whole the sum of all the diagrams contains no contributions to D greater than

$$m_u \left(\frac{\alpha_s}{\pi}\right) \frac{eG_F^2}{(2\pi)^4} \frac{m_q^4}{M_W^2}.$$

The result (10), obtained in Ref. 38 for an individual four-loop diagram, should also be tested for stability when the diagrams of the same type are summed.

We turn again to the result obtained in the three-loop approximation.[39] As a result of summation over all intermediate states, the estimate of the electric dipole moment of the u quark, for example, is determined by the formula

$$|D_u| \sim 2^{-4} \sin\delta\, c_1 c_2 c_3 s_1^2 s_2 s_3 e G_F^2 \alpha_s \pi^{-5} m_0^{-4} M_W^{-2} (m_c^2 - m_t^2)(m_d^2 - m_s^2) \times (m_b^2 - m_d^2)(m_b^2 - m_s^2) m_u^{(k)}, \tag{11}$$

where m_0^2 is a linear combination of m_d^2, m_s^2, and m_b^2, and $m^{(k)}$ is the mass of a constituent quark; the masses without superscripts (k) correspond to current masses.

The appearance in Eq. (11) of factors containing all possible mass differences between quarks of the same charge reflects a general property of the mechanism of CP violation in the Kobayashi-Maskawa theory—there must be not only mixing of all states of the same charge, but also a physical distinction between the states, which in the case of mixing is ensured by the mass difference.

The reasons for the simultaneous presence in Eq. (11) of the constitutent and current masses m_d, m_s, m_c, and m_t are as follows. In loop diagrams containing W-boson propagators the characteristic momenta are of order M_W, and for such values of the momenta the quarks have the current masses. Therefore the differences $m_{qi}^2 - m_{qj}^2$ which occur in the calculation of loops involving a W-boson line contain differences between the squares of the current masses. But the final expression for the matrix element for interaction with the electromagnetic field A_μ has the form

$$M \sim \bar{u}(p)\, \hat{p}\sigma_{\mu\nu} k_\nu \gamma_5 u(p')\, A_\mu,$$

so that in calculating the electric dipole moment for a constituent quark we must assume that

$$\bar{u}(p)\, \hat{p} = m^{(k)} \bar{u}(p).$$

For $\alpha_s(m_{\text{hadr}}^2) \sim 1$, $m_0^2 \sim m_b^2$, $m_s = 150$ MeV, $m_c = 1200$ MeV, $m_d = 10$ MeV, $m_u^{(k)} = 300$ MeV, and

$$\begin{cases} \sin\delta \cdot c_1 c_2 c_3 s_1^2 s_2 s_3 \approx 5\cdot 10^{-5} \; ^{32,40}, \\ m_t \approx 15 \text{ GeV} \end{cases}$$

or

$$\begin{cases} \sin\delta \cdot c_1 c_2 c_3 s_1^2 s_2 s_3 \approx 2\cdot 10^{-5} \; ^{41}, \\ m_t = 30 \text{ GeV}, \end{cases}$$

we obtain

$$|D_u| < 10^{-34} \; e\cdot\text{cm}. \qquad (12)$$

This estimate also holds for the values of s_i and m_t determined in Ref. 42.

This small value of the electric dipole moment of the quark, and hence of the electric dipole moment of baryons, compels us to search for other possible mechanisms leading to an electric dipole moment of a baryon which are also related to the Kobayashi–Maskawa phase.

c) Electric dipole moment of baryons with allowance for exchange forces

The possible appearance of an electric dipole moment of a baryon as a result of interquark exchange forces was first noted in Ref. 36. Subsequent detailed investigation revealed two types of exchange forces.

1) *Exchange forces of type* I. The mechanism of their operation is shown in the diagrams of Fig. 3, where

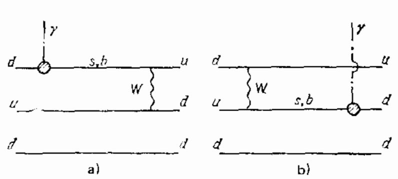

FIG. 3.

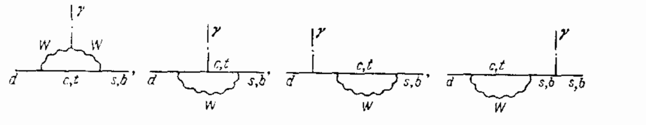

FIG. 4.

the blobs correspond to the amplitude described by the single-loop diagrams of Fig. 4.

The first calculations led to two different estimates of the electric dipole moment of the neutron:

$$D_n \sim 10^{-30} \; e\cdot\text{cm} \; ^{43},$$
$$D_n \sim 10^{-32} \; e\cdot\text{cm} \; ^{44}.$$

Therefore the role of exchange forces was reconsidered in Ref. 45. Technically, the computational scheme of Ref. 45 was similar to that of Ref. 44, where use was made of a picture in which the (ud) diquark with spin 1 interacts with the electric field and the residual d quark is a spectator.

The matrix element for interaction of the diquark (ud) in its rest system with the electric field **E** has the form[45]

$$M \approx \frac{7eG_F^2 f_{K-M} m_0^4}{3\cdot 2^9 \pi^4 M_W^2 \varepsilon} \frac{(m_t^2 - m_c^2)(m_s^2 - m_b^2)}{(m^2 - m_s^2)(m^2 - m_b^2)} \mathbf{p}^2 \mathbf{E} \left[\mathbf{S} - \frac{\mathbf{p}(\mathbf{pS})}{\mathbf{p}^2}\right], \qquad (13)$$

where S is the spin of the diquark, m is the average mass of the u and d quarks, p and ε are the momentum and energy of one of the quarks in the rest system of the diquark, m_0^4 is a dynamical factor, and f_{K-M} is defined by the formula

$$f_{K-M} = \sin\delta \cdot c_1 c_2 c_3 s_1^2 s_2 s_3. \qquad (14)$$

Averaging over the angles in Eq. (13) and using SU(6) nonrelativistic functions for the composite nucleons, we obtain the following value of the electric dipole moment:

$$|D_n| \approx |D_p| \approx \frac{e}{2}\left(\frac{m_t}{M_W}\right)^2 f_{K-M} \cdot 10^{-28} \text{ cm}. \qquad (15)$$

For

$$m_t/m_n = 16 \text{ and } f_{K-M} = 5\cdot 10^{-5} \qquad (16)$$

we have

$$|D_n| \approx 10^{-34} \; e\cdot\text{cm}. \qquad (17)$$

This value is four orders of magnitude smaller than in Ref. 43 and two orders of magnitude smaller than in Ref. 44. It is simplest to establish the reason for the discrepancy between the estimate (17) and the result of Ref. 44. An analysis shows[45] that the reason lies in the overestimate in Ref. 44 by an order of magnitude of the overall coefficient for the matrix element of the photon–diquark interaction, and also in the choice of m as the current mass of the light quark, which does not agree with the assumption of nonrelativistic quarks. It is more difficult to compare the result (17) with the calculations of Ref. 43, in which a different technique was used. However, one of the reasons for the discrepancy is certainly the use in Ref. 43 of an incorrect formula for the amplitude of the $ds\gamma$ and $uc\gamma$ transitions.[1)]

[1)] In connection with this remark, see Ref. 37.

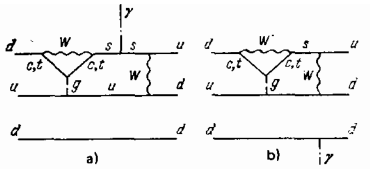

FIG. 5.

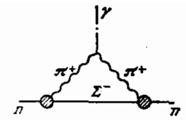

FIG. 7.

The estimate (17) is confirmed by the result of a recent paper by Deshpande *et al.*,[85] who used a computational technique different from that of Refs. 43–45 to calculate the exchange-force contribution. The result of Deshpande *et al.* can be represented in the form

$$|D_n| \approx 2F(m_t)\cdot 10^{-33}\ e\cdot\text{cm}, \tag{18}$$

where the function F, whose argument is the t-quark mass, takes for the values $m_t \approx 20$, 40, 80.5, and ∞ (GeV), respectively, the values $F = 0.029$, 0.087, 0.25, and 2/3. For $m_t = 20$ GeV, Eq. (18) gives an electric dipole moment approximately 2.5 times smaller than Eq. (17).

An estimate of the electric dipole moment of the neutron in agreement with the result (17) was also obtained in Ref. 87.

Thus, exchange forces of type I lead to a value of order $10^{-34}\ e\cdot$cm for the electric dipole moment of the neutron.

2) *Exchange forces of type* II. The mechanism of their operation is described by diagrams of the type shown in Fig. 5, where the broken lines correspond to gluons. This mechanism of generation of an electric dipole moment was studied in two papers,[82,88] which gave different results:

$$D_n \sim 2\cdot 10^{-32}\ e\cdot\text{cm}\ ^{82},$$
$$D_n \sim 10^{-30}\ e\cdot\text{cm}\ ^{88}.$$

To understand the reason for the enhancement of the effect, let us consider the relative values of the amplitudes corresponding to the diagrams of Figs. 5a and 6. Apart from a factor of order unity, the ratio of the contributions to the electric dipole moment from the diagrams of Figs. 5a and 6 is determined by the formula

$$R = \frac{4}{15}\frac{M_W^2}{m_t^2 - m_c^2}\left(\ln\frac{m_t^2}{m_c^2}\right)\frac{q^2(q^2-2pq)}{(q^2-2pq+m_d^2)(q^2-2pq+m_d^2-m_s^2)},$$

where p is the 4-momentum of a quark in the nucleon, q is the 4-momentum running along the gluon line, and m_d and m_s are the masses of the d and s quarks. Putting $|\bar{q}^2| \sim m_\rho^2$ and $m_t = 30$ GeV, we obtain

$$R \approx 12.$$

Since the diagram of Fig. 6 belongs to the class of diagrams which determine the mechanism of operation of the exchange forces of type I, and for $m_t = 30$ GeV

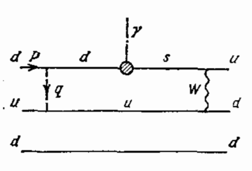

FIG. 6.

these forces led to $D_n \approx 3.5\times 10^{-34}\ e\cdot$cm, we can conclude that the operation of exchange forces of type II increases the value of D_n to

$$D_n \sim 4\cdot 10^{-33}\ e\cdot\text{cm}.$$

This value is five times smaller than that obtained by Khriplovich and Zhitnitsky[82] on the basis of a calculation in the leading approximation in $\ln(m_\pi/M_N)$ of the diagram of Fig. 7, corresponding to inclusion of the single intermediate state $\pi\Sigma$. It is possible that inclusion of nonlogarithmic terms and other intermediate states can reduce the value of D_n obtained in Ref. 82. On the other hand, we cannot exclude the possibility that Eq. (15) underestimates D_n by several times.

From the point of view of the analysis in terms of the factor R determined above, the result of Gavela *et al.*[88] is an overestimate.

Summarizing the situation in the Kobayashi–Maskawa scheme of CP violation, we can conclude that, to all appearances, the expected value of the electric dipole moment of the neutron in this scheme cannot significantly exceed the value

$$D_n \sim 10^{-32}\ e\cdot\text{cm}.$$

3. ELECTRIC DIPOLE MOMENT OF THE NEUTRON IN MODELS OF SPONTANEOUS VIOLATION OF *CP* INVARIANCE. THE WEINBERG MODEL

T. D. Lee[19,20] was the first to draw attention to the possibility of introducing CP noninvariance as an effect due to spontaneous symmetry breaking. Here the initial Lagrangian and the equations of motion for the gauge fields, the fermions, the scalar fields, and their interactions possess CP invariance, and its violation is a consequence of the choice of a certain particular solution. A detailed analysis[10] of the mechanism of spontaneous CP violation was made by Lee for the example of the $O(3)$-symmetric theory of Georgi and Glashow.[46] However, this model was unrealistic, since it contained no experimentally observable weak interaction of the neutral currents. In the case of the $SU(2)_L\otimes U(1)$ model, there is a problem relating to the $\Delta Q = 0$ and $\Delta S = 1$ transitions due to the interaction with the Higgs particles, which must be solved if the corresponding Higgs mesons are to have mass $\gtrsim 10^3$ GeV.[21,23] Since the interaction of the scalar particles becomes strong in the region of such masses, from the computational point of view schemes with heavy bosons do not seem so attractive as schemes with relatively light bosons. An example of schemes of the last type is Weinberg's model of CP violation,[24] to whose detailed discussion we now turn. This model contains no interaction of quark-flavor-changing neutral currents, but at least three doublets of complex Higgs fields are required for its realization.

Suppose that the theory contains only two doublets

$$\tilde{\phi}_1 = \begin{pmatrix} \tilde{\phi}_1^0 \\ \tilde{\phi}_1^- \end{pmatrix} \text{ and } \tilde{\phi}_2 = \begin{pmatrix} \tilde{\phi}_2^0 \\ \tilde{\phi}_2^- \end{pmatrix},$$

with

$$\langle \tilde{\phi}_1 \rangle_0 = \begin{pmatrix} \eta \\ 0 \end{pmatrix}, \text{ but } \langle \tilde{\phi}_2 \rangle_0 = e^{i\varepsilon} \begin{pmatrix} \xi \\ 0 \end{pmatrix}. \tag{19}$$

In order to identify the Goldstone bosons, which must go into the longitudinal degrees of freedom of the vector $W^{\pm}$ and Z^0 bosons, which acquire mass as a result of the spontaneous symmetry breaking, we define new fields obtained by a rotation in the system of the initial fields[93]:

$$\begin{aligned} \phi_1 &= \tilde{\phi}_1 \cos\alpha + \tilde{\phi}_2 e^{-i\varepsilon} \sin\alpha, \\ \phi_2 &= -\tilde{\phi}_1 \sin\alpha + \tilde{\phi}_2 e^{-i\varepsilon} \cos\alpha, \end{aligned} \tag{20}$$

where

$$\sin\alpha = \frac{\xi}{\sqrt{\eta^2 + \xi^2}}.$$

Then only ϕ_1 has a nonzero vacuum expectation value,

$$\langle \phi_1 \rangle_0 = \begin{pmatrix} \sqrt{\eta^2 + \xi^2} \\ 0 \end{pmatrix}, \quad \langle \phi_2 \rangle_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \tag{21}$$

and therefore only ϕ_1 is a "true" Higgs field, whose charged components go into the longitudinal components of the massive $W^{\pm}$ bosons. The quantity $\mathrm{Im}\,\phi_1^0$ goes into the longitudinal component of the massive Z boson. There remain

$$\mathrm{Re}\,\phi_1^0, \quad \mathrm{Re}\,\phi_2^0, \quad \mathrm{Im}\,\phi_2^0, \quad \phi_2^-.$$

In Weinberg's model[24] *CP* violation occurs as a result of transitions of some of the Higgs fields into others and, since the constants for the Yukawa coupling of the Higgs fields to the quarks must be real because of the requirement of *CP* invariance of the initial Lagrangian, the entire violation is determined by the imaginary part of the amplitude for transition between the components of the various doublets. Nothing can be said about the charged component ϕ_2^- in the two-doublet case, and to see that

$$\mathrm{Im}\,\langle \phi_1^0 \phi_2^0 \rangle = 0,$$

it is sufficient to impose the requirement that the potential part $V(\tilde{\phi}_1, \tilde{\phi}_2)$ rewritten in terms of the rotated fields ϕ_1 and ϕ_2 should not contain terms linear in these fields.

In the presence of three doublets of Higgs fields, the physical degrees of freedom are already sufficient for the realization of the mechanism of *CP* violation. Thus, if we have also

$$\phi_3 = \begin{pmatrix} \phi_3^0 \\ \phi_3^- \end{pmatrix},$$

then there can be nondiagonal transitions $\langle \phi_2^- / \phi_3^- \rangle$ and $\langle \phi_2^0 / \phi_3^0 \rangle$, with a nonzero imaginary part.

Weinberg considered the contribution to the electric dipole moments of the quarks from only transitions between the charged Higgs bosons, but in general it is possible to include also the contribution from transitions between the neutral bosons.[25] In order to make a well-defined calculation of the electric dipole moments of the quarks, from which the electric dipole moment of a baryon is constructed, it is necessary to assume that the mechanism of spontaneous *CP* violation is the only one. In that case, the entire violation of *CP* invariance is determined by

$$\mathrm{Im}\,\langle \phi_2^- / \phi_3^- \rangle \text{ and } \mathrm{Im}\,\langle \phi_2^0 / \phi_3^0 \rangle$$

and by finding these amplitudes from the characteristics of *CP* violation in K_L decays it is then possible to calculate the electric dipole moments of the quarks.

We write the part of the Lagrangian corresponding to the interaction of the charged bosons ϕ_3^- and ϕ_2^- with the quarks[27]:

$$\begin{aligned} L = &-\frac{\phi_2^-}{\lambda_2^*} \{ m_d \bar{d}_R [c_1 u_L + s_1 c_2 c_L + s_1 s_2 t_L] \\ &+ m_s \bar{s}_R [-s_1 c_3 u_L + (c_1 c_2 c_3 - s_2 s_3) c_L + (c_1 s_2 c_3 + c_2 s_3) t_L] \\ &+ m_b \bar{b}_R [-s_1 s_3 u_L + (c_1 c_2 s_3 + s_2 c_3) c_L + (c_1 s_2 s_3 - c_2 c_3) t_L] \} \\ &+ \frac{\phi_3^+}{\lambda_3} \{ m_u \bar{u}_R [c_1 d_L - s_1 c_3 s_L - s_1 s_3 b_L] \\ &+ m_c \bar{c}_R [s_1 c_2 d_L + (c_1 c_2 c_3 - s_2 s_3) s_L + (c_1 c_2 s_3 + s_2 c_3) b_L] \\ &+ m_t \bar{t}_R [s_1 s_2 d_L + (c_1 s_2 c_3 + c_2 s_3) s_L + (c_1 s_2 s_3 - c_2 c_3) b_L] \} + \mathrm{H.c.}, \end{aligned} \tag{22}$$

where $\lambda_2 = \langle \phi_2^0 \rangle$ and $\lambda_3 = \langle \phi_3^0 \rangle$, and $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$ are the mixing parameters in the six-quark system. The *CP* violation is characterized by the quantity[2)]

$$\mathrm{Im}\,A(0) \equiv \mathrm{Im}\,\frac{\langle 0 | T(\phi_2^- \phi_3^-) | 0 \rangle_{q=0}}{\lambda_2^* \lambda_3}, \tag{23}$$

which is related to the K_L-decay parameter ε by the equation[26,27]

$$\varepsilon \approx -0.037 \frac{\mathrm{Im}\,A(0)\, m_K^2}{G_F} e^{i\varphi}, \quad \varphi = \tan^{-1}\left(\frac{2\Delta m_K}{\Gamma_S}\right) \tag{24}$$

or

$$\mathrm{Im}\,A(0) = \frac{G_F}{m_0^2}, \quad m_0 \approx 2 \text{ GeV}. \tag{25}$$

It follows from this expression that the masses of the charged Higgs mesons should not be large[27]:

$$m_2 \approx 2 - 3 \text{ GeV}, \quad \sqrt{m_2 m_3} < 30 \text{ GeV}.$$

The diagrams corresponding to interaction of the dipole moment with the electric field are shown in Fig. 8. The formulas for the electric dipole moments of the quarks have the form

$$D_d = -\frac{e m_d}{24\pi^2} \mathrm{Im}\,A(0) [m_u^2 c_1^2 L(m_u) + m_c^2 s_1^2 c_2^2 L(m_c) + m_t^2 s_1^2 s_2^2 L(m_t)], \tag{26}$$

$$D_u = -\frac{e m_u}{48\pi^2} \mathrm{Im}\,A(0) [m_d^2 c_1^2 L(m_d) + m_s^2 s_1^2 c_3^2 \cdot L(m_s) + m_b^2 s_1^2 s_3^2 L(m_b)], \tag{27}$$

$$\begin{aligned} D_s = \frac{e m_s}{24\pi^2} \mathrm{Im}\,A(0) [&m_u^2 s_1^2 c_3^2 L(m_u) + m_c^2 (c_1 c_2 c_3 - s_2 s_3)^2 L(m_c) \\ &+ m_t^2 (c_1 s_2 c_3 + c_2 s_3)^2 L(m_t)], \end{aligned} \tag{28}$$

where[3)]

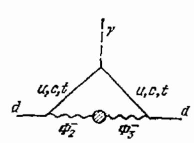

FIG. 8.

[2)] The mixing of the neutral Higgs mesons leads to corrections $\sim m_{u,d}^2 \cot^2\theta_C / m_{c,s}^2$.

[3)] In connection with the calculation of $L(m_q)$, see also Ref. 28.

$$L(m_q) \approx \frac{m_2^2 m_3^2}{m_3^2 - m_2^2}\left\{\frac{1}{(m_2^2 - m_q^2)^3} m_2^4 \left(\ln\frac{m_2^2}{m_q^2} - \frac{3}{4}\right) - (m_2 \to m_3)\right\}.$$

The electric dipole moment of the neutron in the model of valence quarks is determined by the formula $D_n = (4/3)D_d - (1/3)D_u$ and, since the existing limits on s_i and c_i (Refs. 32, 40, and 41) give $D_u \ll D_d$, the electric dipole moment of the neutron has the value

$$D_n \approx \frac{e \operatorname{Im} A(0)}{18\pi^2} m_d m_c^2 L(m_c) s_1^2 = 2.6 \cdot 10^{-25} L(m_c)\, e \cdot \mathrm{cm}. \qquad (29)$$

For m_2 and m_3 lying in the intervals $2.5 \leq m_2 \leq 5$ GeV and $5 \leq m_3 \leq 20$ GeV, we have

$$D_n \approx (1 - 3) \cdot 10^{-25}\ e \cdot \mathrm{cm}. \qquad (30)$$

This value is close to the experimental value of the upper limit and provides grounds for believing that inclusion of an admixture of $\bar{s}s$ pairs in the nucleon can lead to an even larger value of D_n. According to Eqs. (26)–(28), the electric dipole moment of the s quark is approximately 400 times larger than that of the d quark, and even a small admixture of $\bar{s}s$ pairs should change the value of D_n. According to the estimates of Zhitnitskiĭ and Khriplovich,[28] the main contribution to D_n comes from intermediate states containing strange particles, $\Sigma^- K^+$, and[4)]

$$D_n \approx -9 \cdot 10^{-25}\ e \cdot \mathrm{cm}. \qquad (31)$$

This value is already somewhat larger than the experimental value

$$D_n^{\exp} < 6 \cdot 10^{-25}\, e \cdot \mathrm{cm}^{11},$$

and before long it will be possible to establish whether the electric dipole moment of the neutron is really induced by spontaneous *CP* violation alone.

The electric dipole moment of the neutron is not the only quantity in Weinberg's model of *CP* violation for which the theoretical prediction is in conflict with the experimental limit. A second characteristic which is also not easily accommodated within the experimental limits is the ratio of the parameters ε' and ε of *CP* violation in $K_L \to 2\pi$ decays. Experimentally, this ratio has the value[86]

$$|\varepsilon'/\varepsilon| = 0.007 \pm 0.013.$$

According to an estimate of Anselm and D'yakonov[26] in the Weinberg model, we have

$$|\varepsilon'/\varepsilon| \approx 0.02.$$

This ratio can still be regarded as consistent with the experimental value within the errors of the measurements. But there have recently appeared claims that Weinberg's model predicts a much larger ratio ε'/ε. According to Deshpande,[47]

$$\varepsilon'/\varepsilon \approx -0.045,$$

while a calculation of Sanda[48] gives

$$0.048 < |\varepsilon'/\varepsilon| < 0.050.$$

However, the calculations of Deshpande and Sanda are not free of theoretical uncertainties.

4)Here we give the value of D_n from Ref. 82, obtained by reconsidering the calculations of Ref. 28.

In connection with the problem arising from the fact that the theoretical predictions for D_n and ε'/ε lie above the experimental limits, it is appropriate to recall that in the six-quark $SU(2)_L \otimes U(1)$-symmetric scheme another mechanism of *CP* violation is operative—the Kobayashi–Maskawa mechanism. It is quite possible that it is this mechanism that determines the picture of *CP* violation in K_L decays, in which case, instead of Eq. (25), there follows the inequality

$$\operatorname{Im} A(0) \ll \frac{G_F}{m_0^2}, \text{ where } m_0 \approx 2 \text{ GeV},$$

while for the ratio ε'/ε we obtain the value $\sim 10^{-3}$.[32,80,81]

The simultaneous operation of the phase mechanism and the mechanism of spontaneous *CP* violation in this case can induce any values of the electric dipole moment less than $10^{-25}\ e \cdot$ cm, and observation of an electric dipole moment in the range

$$10^{-32} \ll D_n < 10^{-25}\ e \cdot cm$$

can be regarded as evidence for the combined operation of the two mechanisms.[45,49] Nevertheless, certain intervals of values within this range can also be explained in other models.

4. ESTIMATES OF THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON IN OTHER GAUGE MODELS

The first model of *CP* violation in a gauge theory, based on a mechanism of direct *CP* violation due to the complex character of the coupling constants, was proposed by Mohapatra.[13] At that time, it was assumed that there exist only four quarks. Therefore, to ensure that the theory contained a phase having physical significance, Mohapatra introduced, besides the left-helicity doublets, one right-helicity doublet of quarks:

$$\binom{u}{d\cos\theta + s\sin\theta}_L, \quad \binom{c}{-d\sin\theta + s\cos\theta}_L, \quad \binom{c}{d\cos\phi + is\sin\phi}_R.$$

With this choice there is an interaction of the Z boson with the $(\Delta Q = 0, \Delta S = 1)$ current, and to suppress this interaction it is necessary to take $\phi \sim 10^{-4}$. The Higgs sector includes a doublet of complex fields and a triplet of real fields. The original estimate obtained by Mohapatra for the electric dipole moment of the quark, $D_{u,d} \sim 10^{-23}\ e \cdot$ cm, was re-examined by Pais and Primack,[14] who obtained $D_u \sim 10^{-28}\ e \cdot$ cm. Subsequently, Wolfenstein[70] put forward arguments according to which in this model the electric dipole moment of the neutron should have a value of order 10^{-24}–$10^{-25}\ e \cdot$ cm.

The possibility of *CP* violation in interactions of gauge fields was also discussed by Pais,[71,72] who studied the $O(4)$-symmetric scheme of gauge theory. However, this scheme encountered difficulties in the description of the experimental data, since it predicts a strong suppression of the $(\bar{\nu}_\mu \nu_\mu)$(ee) interaction, which is not confirmed by experiment.

A mechanism of *CP* violation due to complex constants for interaction with gauge fields has also been introduced in papers devoted to the investigation of $SU(2)_L \otimes SU(2)_R \otimes U(1)$-symmetric models of the electroweak interaction. Before the spontaneous symmetry breaking, these models have left-right symmetry. As a result of the spontaneous symmetry breaking, the vector fields associated with the right-helicity currents acquire a much larger mass than the vector fields which interact with the left-helicity currents. This explains the explains the experimental absence of V+A weak interactions. The Higgs sector includes at least two doublets of complex scalar fields.

By studying a four-quark $SU(2)_L \otimes SU(2)_R \otimes U(1)$-symmetric model with *CP* violation, Frenkel and Ebel[16] obtained for the electric dipole moment of a constituent quark the estimate

$$D_d \sim \sin \alpha_{L,R} \cdot 10^{-26}\ e \cdot \mathrm{cm},$$

where $\alpha_{L,R}$ is the phase difference between the coupling constants associated with the left- and right-helicity currents. In general, in the $SU(2)_L \otimes SU(2)_R \otimes U(1)$-symmetric theory, *CP* violation can also occur in the sector of Higgs interactions. In Ref. 16 the contribution of the Higgs bosons was suppressed in relation to the contribution of the vector bosons by means of the special requirement $m_{\mathrm{Higgs}} \gtrsim m_W$. But in other schemes, for example, in the scheme of Mohapatra, Pati, and Wolfenstein,[17] the largest contribution to the *CP* violation comes, on the contrary, from the interactions of Higgs bosons. These give a contribution to the electric dipole moment of the neutron of order $10^{-29}\ e \cdot$cm, whereas the contribution from the vector bosons is of order $10^{-35}\ e \cdot$cm. The scheme of Mohapatra, Pati, and Wolfenstein is one of a number of schemes which give a picture of a superweak interaction. Another such scheme is that of Sikivie,[21] which admits a quark-flavor-changing neutral-current interaction. At ordinary energies this interaction is very weak, since the masses of the corresponding intermediate bosons are assumed to be very large. Assuming that the imaginary part of the mass matrix for the $K^0 - \bar{K}^0$ transition originates from the interaction

$$g B^0 \bar{n} (c_1 + c_2 \gamma_5) \lambda + \mathrm{H.c.},$$

where c_1 and c_2 are complex constants and B^0 is an intermediate boson, we can obtain a bound on the effective constant of the four-fermion interaction with $\Delta S = 2$ and then use the resulting estimate to determine the electric dipole moment of the neutron. According to Sikivie,[21] $D_n \sim 10^{-30}\ e \cdot$cm.

A similar model, but with a microweak violation of *CP* invariance, was proposed by Lahanas and Vayonakis,[23] who obtained the estimate $D_n \sim 10^{-26}\ e \cdot$cm for the electric dipole moment of the neutron.

It should be noted that in most of the papers enumerated in the present section the electric dipole moment of the neutron was estimated simply on the basis of dimensional arguments with allowance for the magnitudes of the *CP*-violating phases and constants. A more detailed study for the $SU(2)_L \otimes SU(2)_R \otimes U(1)$-symmetric model of Mohapatra and Pati[15] was made by Beall and Soni,[75] who obtained the estimate

$$D_n \sim 10^{-22}\ |\eta_{+-} - \eta_{00}|\ e \cdot \mathrm{cm} \sim 10^{-25}\ e \cdot \mathrm{cm}.$$

The predictions of the various schemes of *CP* violation in the gauge theory of the electroweak interaction are collected together in Table I.

TABLE I. Electric dipole moment of the neutron in various gauge models of the electroweak interactions.

Symmetry group	Sector of the theory in which *CP* is violated	Value of D_n/e, cm	References
$SU(2)_L \otimes SU(2)_R \otimes U(1)$	$SU(2)_R$ gauge interaction without the GIM mechanism	$\left(\frac{m_q^{\mathrm{const}}}{M_N}\right) \cdot \begin{cases} 10^{-23} \\ 10^{-28} \\ 10^{-24} \end{cases}$	13 14 70
O(4) No $\nu_\mu e \to \nu_\mu e$	Gauge interaction		71, 72
$SU(2)_L \otimes SU(2)_R \otimes U(1)$	Gauge interaction + Higgs interactions	10^{-24} 10^{-25}	15 75
$SU(2)_L \otimes SU(2)_R \otimes U(1)$	Gauge interaction	$\sin \Delta\alpha_{L,R} \cdot 10^{-26}$	16
$SU(2)_L \otimes SU(2)_R \otimes U(1)$	Gauge interaction Higgs interactions	10^{-35} 10^{-29}	17
$SU(2)_L \otimes U(1)$	Higgs interactions without the GIM mechanism	10^{-26}	23
$SU(2)_L \otimes U(1)$	Higgs interactions without the GIM mechanism	10^{-30}	21
O(3) No interaction of neutral currents	Higgs interactions	10^{-23}	20
$SU(2)_L \otimes U(1)$	Higgs interactions with the GIM mechanism	$\sim 10^{-24}$ $= (1-3) \cdot 10^{-25}$ $\sim 9 \cdot 10^{-25}$	24 26, 27 28, 82
$SU(2)_L \otimes U(1)$ Six quarks	Gauge interaction	10^{-31} $2 \cdot 10^{-32}$ 10^{-30}	37, 45, 85, 87 82 88
$SU(2)_L \otimes U(1)$ Six quarks	Gauge interaction + spontaneous *CP* violation	$10^{-31} < \frac{D_N}{e} < 10^{-25}$	45

For references to earlier papers in which the electric dipole moment of the neutron was also estimated prior to the construction of gauge-invariant renormalizable models of the theory, the reader may refer to the paper of Dress *et al.*[12]

It can be seen from Table I that the discovery of an electric dipole moment of the neutron in the range of values $10^{-25}-10^{-30}\ e \cdot$cm may not give an unambiguous answer to the question of what symmetry group and what mechanism of *CP* violation are realized in nature. However, the absence of an electric dipole moment of the neutron up to values $10^{-32}\ e \cdot$cm would indicate that the violation of *CP* invariance is due to the phase mechanism of Kobayashi and Maskawa.

5. ELECTRIC DIPOLE MOMENT OF THE NEUTRON IN QUANTUM CHROMODYNAMICS

Another source of *CP* violation is contained in quantum chromodynamics, which is used for the description of the strong interactions. In this theory, the strong interactions occur as a result of the interaction of colored quarks and colored gluons, where the gluons form a system of Yang–Mills fields. The investigation of the ground states of this system led to the conclusion that there exists an infinite set of vacua[52] distinguished by different topological charges, which acquire physical significance because of the presence of so-called instanton solutions[53] corresponding to the transition from the vacuum with topological charge n to the vacuum with topological charge $n+1$. Tunneling between different vacua removes the degeneracy, as a result of which there occurs an infinite set of orthogonal vacuum states with energy depending on a continuous parameter θ taking values from 0 to π, and the presence of the θ vacua makes it necessary to include in the Lagrangian of QCD an additional term having the form[54]

$$L^{\theta}=-\theta\frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^a_{\mu\nu}. \quad (32)$$

In formal language, the dependence on the parameter θ occurs in the following way. The usual way of writing the Lagrangian of the gluon fields in the form

$$L=-\frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} \quad (33)$$

does not uniquely fix the Lagrangian density—it is possible to add to this Lagrangian a term which is a total divergence. The quantity L^{θ} is just such a total divergence:

$$F^a_{\mu\nu}\tilde{F}^a_{\mu\nu}=\partial_\mu K_\mu,$$
$$K_\mu=2\varepsilon_{\mu\nu\lambda\sigma}A^a_\nu\left(\partial_\lambda A^a_\sigma+\frac{g}{3}f^{abc}A^b_\lambda A^c_\sigma\right). \quad (34)$$

Terms of the Lagrangian which represent a total divergence are usually neglected, since they give a contribution to the action which is determined by an integral over a sphere of infinitely large radius,

$$\int d^4x\,\partial_\mu K_\mu(x)\to\int d^3S_\mu K_\mu,$$

and for sufficiently rapid decrease of the solutions with increasing radius such an integral vanishes.

In a non-Abelian theory, however, there exist solutions—instantons[53]—which do not have sufficiently rapid decrease, so that

$$\int_\theta d^3S_\mu K_\mu\,|_{\text{inst}}\neq 0.$$

Therefore θ can have physical significance, and this significance is clear: since $F^a_{\mu\nu}$ and the dual tensor $\tilde{F}^a_{\mu\nu}$ have opposite P and T parities, the presence of L^{θ} should lead to a violation of CP invariance in the strong interactions. The reader can find a detailed analysis of the need for the θ term in non-Abelian theories in the reviews of Refs. 55, 56, and 69, and here we shall consider only possible consequences of the existence of the θ term for the electric dipole moments of baryons. Several methods of estimating the electric dipole moment of the neutron exist in the literature, and they all lead to the conclusion that L^{θ} with $\theta\neq 0$ gives a catastrophically large value for the electric dipole moment of the neutron, which can be reconciled with the experimental values only if $\theta<10^{-9}$.

Such a small value of the parameter θ, which in chromodynamics can take values from 0 to π, makes it desirable as a first priority to modify the theory in such a way that in it θ is automatically equal to zero. Investigations have shown that in such a theory either at least one of the quarks must have zero mass[57] or the theory must contain light neutral pseudoscalar particles—axions.[58,59]

The first possibility encounters difficulties in the calculation of the meson masses in terms of the quark masses by the methods of current algebra,[60] and experimental searches for axions[61] have so far had no success.[5)] The experiments have verified the predictions of the simplest schemes proposed by Weinberg[58] and Wilczek.[59] There exist methods of introducing a global U(1) symmetry[57] leading to elimination of the θ term, for which the axion is practically unobservable. In one of the methods,[62] it is assumed that the axion interacts only with very heavy hypothetical quarks, and as a consequence of this its production in collisions of ordinary particles is forbidden. Another method[63,79] allows a significant reduction in the axion–quark interaction constant, at the price of an enlargement of the Higgs sector of the theory.

It has recently been shown[73,84] that in the SU(5) unified model of the electroweak and strong interactions the introduction of an additional global U(1) symmetry which eliminates the θ term leads to the appearance of very light axions with a coupling constant of order f_π/M_X, where $M_X\sim 10^{15}$ GeV. These axions are practically sterile and, as was shown in Ref. 84, their production mechanism makes it possible not only to solve the problem of the θ term, but also to explain the hierarchy of masses in the various fermion multiplets.

In connection with attempts to solve the problem of a strong violation of CP invariance without axions, mention should be made of an idea of Polyakov, according to which the result of a nonzero contribution of the θ term to the CP violation can be a consequence of taking into account only single instantons and should disappear after summation over multi-instanton configurations. An investigation of Yang-Mills systems in a space of 2 +1 dimensions shows that just such a situation obtains in that case.[64]

However, in the case of 4-dimensional space there exist arguments[62] that the θ term should lead to observable effects. It is not obvious that the θ term leads to observable effects because it is impossible to calculate these effects in the framework of quark–gluon perturbation theory, since the product $F^a_{\mu\nu}\tilde{F}^a_{\mu\nu}$ contain gluon vertices which are equal to zero either by virtue of the conservation of 4-momentum or by virtue of the antisymmetrization with respect to identical fields. For example, in an SU(2)-symmetric theory including a triplet of vector fields W^+, W^-, and W^0 the product $F^a_{\mu\nu}\tilde{F}^a_{\mu\nu}$ contains vertices of the type

$$\varepsilon_{\mu\nu\sigma\tau}k^+_\mu k^-_\sigma W^+_\nu W^-_\tau,$$
$$\varepsilon_{\mu\nu\sigma\tau}k^0_\mu k^0_\sigma W^0_\nu W^0_\tau,$$
$$\varepsilon_{\mu\nu\sigma\tau}(k^++k^-+k^0)_\mu W^+_\nu W^-_\sigma W^0_\tau,$$
$$\varepsilon_{\mu\nu\sigma\tau}W^+_\mu W^-_\sigma W^0_\nu W^0_\tau\ \text{etc.},$$

where k^+, k^-, and k^0 are the 4-momenta of the W^+, W^-, and W^0 bosons, all the momenta being taken as incoming.

How can we calculate in this case any CP-odd effect induced by the θ term?

---

5)See, however, Ref. 76.

Several proposals exist in the literature:

1) Since the physical violation of CP invariance should be due to effects which occur outside perturbation theory, one can estimate the ratio of the electric dipole moment to the magnetic moment as the ratio of the corresponding vacuum expectation values:[62]

$$\left|\frac{D}{\mu}\right| \sim \left|\frac{\langle 0 \mid F^a_{\mu\nu}\tilde{F}^a_{\mu\nu} \mid 0\rangle}{\langle 0 \mid F^a_{\mu\nu}F^a_{\mu\nu} \mid 0\rangle}\right| \approx 2\cdot 10^{-2}\theta. \qquad (35)$$

Here, however, there is no proof that the vacuum expectation value $\langle 0 | F^a_{\mu\nu}\tilde{F}^a_{\mu\nu} | 0\rangle$ must really lead to the appearance of the interaction

$$\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi\, \partial_\nu A_\mu,$$

nor is there a proof that the magnetic moment is determined by the vacuum expectation value $\langle 0 | F^a_{\mu\nu}F^a_{\mu\nu} | 0\rangle$.

2) Since it is the instantons that give physical meaning to the concept of the θ vacuum, and these instantons are nonperturbative solutions, one can calculate the electromagnetic vertex of a quark in the presence of instantons. Then, as usual, the electric dipole moment of a baryon is constructed from the electric dipole moments of the individual quarks. The CP-odd part of this vertex is found to have the form[67]

$$\hat{V}_\mu(CP=-1) = i\sin\theta\cdot\frac{d}{m}(\hat{p}_2\gamma_\mu + \gamma_\mu\hat{p}_1)\gamma_5, \qquad (36)$$

where d is some integral of the density of instantons, m is the mass of a constituent quark, θ is the phase of the θ vacuum, and p_2 and p_1 are the 4-momenta of the final and initial quarks. This result, obtained in Ref. 67 by means of complicated calculations, can be reproduced in a simpler way. For this, the θ dependence must be transferred from the gluon part to the quark part of the Lagrangian. Owing to the presence of triangle anomalies,[68] it is possible to do this by means of a chiral transformation on the ψ functions of the quarks, and as a result it is found that

$$\delta L^\theta_q(CP=-1) = im_0\sum_j \bar{q}_j\gamma_5 q_j, \qquad (37)$$

where

$$m_0 = \theta\,\frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s}. \qquad (38)$$

The form of δL^θ_q is determined by the requirement that the CP-odd part of the quark Lagrangian, just as L^θ, is a singlet in the space of quark flavors.

Taking into account the interaction (37), the electromagnetic vertex of a quark is determined by the diagrams of Fig. 9, and its CP-odd part has the form

$$\hat{V}'_\mu(CP=-1) = \frac{im_0}{2m^2}(\hat{p}_2\gamma_\mu + \gamma_\mu\hat{p}_1)\gamma_5, \qquad (39)$$

where m_0 is determined by Eq. (38) and m is the quark mass (for a constituent quark, m is the constituent quark, m is the constituent mass). The structures of $\hat{V}_\mu(CP=-1)$ and $\hat{V}'_\mu(CP=-1)$ are identical, which reflects the equivalence of the computational methods. A defect of both operators $\hat{V}_\mu$ and $\hat{V}'_\mu$ is the fact that they

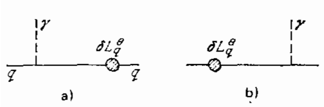

FIG. 9.

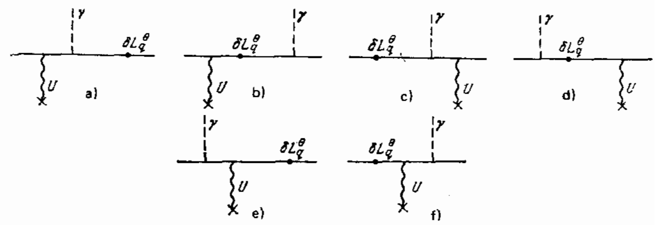

FIG. 10.

give zero when sandwiched between wave functions of free quarks. In order to somehow obtain an estimate of the electric dipole moment in spite of this, the authors of Ref. 67 sandwiched the operator $\hat{V}_\mu$ between wave functions of quarks in a spherical Coulomb-like field U. In the limit of weak coupling, they obtained a nonzero result for the electric dipole moment of the quark, but, as is clearly seen in working with δL^θ_q instead of L^θ, this result may be a consequence of treating the operator $\hat{V}_\mu(CP=-1)$ as a local operator. In perturbation theory, the contribution from the diagrams of Figs. 10a–10d, corresponding to allowance for a weak coupling of the quarks, is compensated by the contribution from the diagrams of Figs. 10e and 10f.

3) We turn now to the work of Baluni,[65] who was one of the first to investigate the influence of the θ term on the electric dipole moment of the neutron. Using instead of L^θ the Lagrangian $\delta L^\theta_q(CP=-1)$ defined according to Eq. (37), Baluni noted that in the presence of this term the nucleon becomes a mixture of states of opposite parity:

$$| n\rangle = | N\rangle + \sum_* (M^* - M)^{-1} | N^*\rangle\langle N^* | \delta L^\theta_q | N\rangle,$$

where M and M^* are the masses of the states $(1/2^+)$ and $(1/2^-)$, and the summation goes over all possible physical states with the quantum numbers $(1/2^-)$. Baluni determined the electric dipole moment in accordance with the formula

$$\mathbf{D}_n = 2\sum (M^* - M)^{-1}\,\mathrm{Re}\,\langle N | \mathbf{d} | N^*\rangle\langle N^* | \delta L^\theta_q | N\rangle, \qquad (40)$$

where d is the dipole-moment operator allowed in the transitions $(1/2^+)\to(1/2^-)$ without any CP violation.

Taking into account the nearest resonances $N^*(1/2^-) = S'_{11}$ and S''_{11} as the intermediate states and performing the calculations in the bag model, Baluni obtained the result[6)]

$$D_n \approx 2.7\cdot 10^{-16}\,|\,\theta\,|\; e\cdot\mathrm{cm}. \qquad (41)$$

However, we shall see from the following discussion that the intermediate states corresponding to the continuous spectrum give D_n of the same order of magnitude, as a consequence of which the degree of reliability of the resulting estimate remains unclear.

4) The work of Crewther *et al.*[66] is considered to be the most rigorous proof that the θ term actually gives a nonzero contribution to the electric dipole moment of the neutron. These authors used the following expression for the initial Lagrangian of the meson–nucleon theory:

[6)] We give the value corresponding to the standard definition of $\delta L^\theta_q(CP=-1)$.

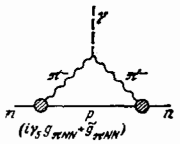

FIG. 11.

$$L=\bar{\psi}_N i\gamma_\mu\partial_\mu\psi_N-\bar{\psi}_N m\psi_N-ig_{\pi NN}\bar{\psi}_N\gamma_5\tau\psi_N\pi+\ldots \quad (42)$$

They found that in the presence of δL_q^θ defined by Eq. (37) the πNN vertex acquires the CP-noninvariant form

$$\bar{\psi}_N\tau(i\gamma_5 g_{\pi NN}+\tilde{g}_{\pi NN})\psi_N\pi \quad (43)$$

with $\tilde{g}_{\pi NN}/g_{\pi NN}\approx 0.002$.

Studying further the diagrams with different numbers of pions in the intermediate state, it was noted in Ref. 66 that in the limit of chiral symmetry ($m_\pi\to 0$) the electric dipole moment of the neutron is determined solely by the single diagram of Fig. 11, since the corresponding amplitude has a factor $\ln(M_N/m_\pi)$, which is absent in the other amplitudes. Calculating the contribution from the diagram of Fig. 11 to the electric dipole moment of the neutron, Crawther *et al.* found that

$$D_n\approx 3.6\cdot 10^{-16}\theta\ e\cdot\text{cm}. \quad (44)$$

Since in Ref. 66 the object of attention is the πNN vertex, it might appear that the result for D_n does not depend on the properties and interactions of the other mesons, in particular the η and η' mesons. This is not so. It is known (see, for example, Ref. 62) that if for the η and η' mesons in QCD it were not necessary to solve the so-called $U(1)$ problem,[91] i.e., if it were not necessary to introduce a special mechanism to generate the masses of these particles, then the θ term would not lead to the physical effects of CP violation.

The relation between the quantity D_n and the solution of the $U(1)$ problem was demonstrated in Ref. 92 for the example of a nonlinear chiral model containing a nonet of baryons and a nonet of pseudoscalar mesons. In the presence of the θ term, the meson–nucleon part of Lagrangian of the model in the approximation linear in the pions has the form

$$L=\bar{\psi}_N(i\gamma_\mu\partial_\mu-m_N-g_{\pi NN}i\gamma_5\tau\pi)\psi_N$$
$$+ia\left(\theta-\sum_j\Phi_j\right)\left\{\frac{F_\pi}{\sqrt{2}}(\gamma+\delta)\bar{\psi}_N\gamma_5\psi_N+i\delta\bar{\psi}_N\tau\psi_N\pi\right\}, \quad (45)$$

where the coefficients γ and δ are expressed in terms of the mass splitting in the baryon octet, and the coefficient a characterizes the degree of solution of the $U(1)$ problem, i.e., it determines by how much the masses of the η and η' mesons are displaced with respect to the mass of the K meson. We note that besides the CP-odd renormalization of the πNN vertex [cf. Eq. (43)] the θ term leads also to a CP-odd renormalization of the nucleon mass term, as a consequence of which the real effect of CP violation is determined by the difference of the CP-odd phases of the πNN vertex and the mass term. Calculations with the Lagrangian (45) lead to the estimate (44).

Another chiral model, which includes nucleons as well as pseudoscalar and scalar mesons and which makes it possible to study the dependence of D_n on the solution of the $U(1)$ problem, was considered in Ref. 94.

The result of all the investigations is the conclusion that the θ term can induce an electric dipole moment of the neutron of order

$$|D_n|\sim(10^{-15}-10^{-16})\,|\theta|\ e\cdot\text{cm}.$$

However, the concrete value of D_n remains quite uncertain, since, as can be seen by comparing the results (41) and (44), the amplitudes enhanced by the factor $\ln(m_N/m_\pi)$ give a contribution comparable with the contribution of the nonenhanced amplitudes, and the latter are very numerous.

If in the future the uncertainties in the concrete coefficient in converting the value of θ to the value of D_n are successfully eliminated, it will be possible by measuring D_n to test the theoretical schemes which permit a calculation of θ. As was shown by Ellis *et al.*,[89] this possibility arises in the SU(5)-symmetric scheme of grand unification of the electroweak and strong interactions. This scheme offers an explanation for the baryon asymmetry of the Universe if, together with the nonconservation of baryon number which is characteristic of the scheme, there occurs a violation of CP invariance. But the CP violation can be expressed in terms of the θ term determined by the CP-odd component of the quark masses. In the SU(5) scheme with the minimum number of Higgs scalar particles, the same renormalizations determine the evolution of the parameter θ and the production of the excess of baryons over antibaryons. Therefore we have a relation between the ratio n_B/n_γ and theparameter θ:

$$\theta_{QCD}\ (1\ \text{GeV})\gtrsim 6\cdot 10^{-3}\,(n_B/n_\gamma).$$

Using the data on the value of n_B/n_γ and the coefficient of proportionality between θ and D_n calculated by Baluni[65] and by Crewther *et al.*,[66] Ellis *et al.*[89] obtained a lower limit on the electric dipole moment of the neutron:

$$D_n\gtrsim 2{,}5\cdot 10^{-18}\,(n_B/n_\gamma)\gtrsim 3\cdot 10^{-28}\ e\cdot\text{cm}.$$

It might appear that this limit requires the abandonment of all schemes of CP violation which predict a smaller value for the electric dipole moment of the neutron. However, first of all, as follows from the foregoing, there is still some uncertainty in the coefficient of proportionality between θ and D_n, and secondly, when the Higgs sector of the SU(5)-symmetric scheme of grand unification is extended there is no longer a well-defined relation between the ratio n_B/n_γ and the parameter θ. This can be seen, in particular, for the examples of the SU(5)-symmetric models considered in Refs. 73 and 84, where an additional global U(1) symmetry of the Higgs interactions leads to vanishing of the effective value of the parameter θ but does not forbid a nonzero value of the ratio n_B/n_γ.

6. CONCLUSIONS

The investigation of the possible mechanisms of generation of an electric dipole moment of the neutron leads to the following conclusions, which it makes sense to list in the order opposite to that in which they occur in the exposition.

1. The electric dipole moment of the neutron resulting from the presence of the θ term in QCD is of order

$$(10^{-15} - 10^{-16}) \mid \theta \mid e\cdot\text{cm}.$$

This means that it is necessary to consider only those variants of the theory in which the effective value of θ is very small ($\theta < 10^{-9}$) or exactly equal to zero.

The possibility for this exists in certain schemes including light pseudoscalar particles—axions, which are sterile with respect to interaction with the ordinary hadrons (Refs. 62, 63, 73, 74, 79, 84, and 90).

2. The mechanism of spontaneous *CP* violation, whose most attractive realization is achieved in Weinberg's model,[24] predicts values of D_n which in fact lie within the range of experimental resolution in the measurement of D_n. Therefore an increase in the experimental accuracy by several times would provide a direct answer to the question of whether this mechanism is universal in the phenomenon of *CP* violation in K_L decays and in the phenomenon of *CP*-odd interaction of photons with nucleons through the electric dipole moment. Being a model of milliweak violation of *CP* invariance, Weinberg's model may now already be encountering difficulties in explaining the ratio ε'/ε of the parameters characterizing the *CP* violation in K_L decays.[47,48] These difficulties are absent in some other models involving spontaneous *CP* violation[21,23]; in them, however, the Higgs mesons must have such large masses that the theory lies at the limit of applicability of perturbation theory.

Finally, it should be stressed that all the models of spontaneous *CP* violation entail the difficulty associated with the hitherto unsolved problem of the splitting of the Universe into domains, which is predicted in such models.[83]

3. The mechanism of *CP* violation due to the complex character of the individual constants for interaction of the quarks with the gauge fields, being introduced in the $SU(2)_L \otimes U(1)$-symmetric scheme through the Kobayashi-Maskawa phase, encounters no difficulties in explaining the values of the parameters of *CP* violation in K_L decays. The value of the electric dipole moment of the neutron predicted by this mechanism, $D_n \sim 10^{-32}\, e\cdot\text{cm}$, is far from the region accessible to contemporary experiment.

But in the case of the $SU(2)_L \otimes SU(2)_R \otimes U(1)$-symmetric models,[13-16,70,75] the *CP* violation due to the complex character of the constants for interaction of the gauge fields can induce much larger values of the electric dipole moment of the neutron.

Returning to the $SU(2)_L \otimes U(1)$-symmetric schemes, it should be added that if we overlook the objections of a cosmological character and allow operation of the mechanism of spontaneous *CP* violation simultaneously with the Kobayashi-Maskawa phase mechanism, then the theory admits the possibility of explaining any values of the electric dipole moment of the neutron in the interval from $10^{-25}\, e\cdot\text{cm}$ to $10^{-32}\, e\cdot\text{cm}$.[45,49]

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