SOVIET PHYSICS USPEKHI VOLUME 11, NUMBER 4 JANUARY-FEBRUARY 1969

539.12.01

# *MODELS FOR VIOLATION OF CP INVARIANCE*

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Usp. Fiz. Nauk 95, 460–469 (1968)

THIS report deals with models for the violation of CP invariance and discusses experiments needed to decide in what interactions is CP invariance violated. We wish from the very beginning to make the reservation that one must not exclude the possibility that the violation occurs not in one but in several interactions at the same time. In that case the already complicated problem becomes even more complicated and for this reason we suppose in what follows that the violation proceeds in one place only.

The classification of models for the violation of CP invariance according to the strength of interaction has been discussed repeatedly and there is no need to again consider it in detail. We shall simply give a list of possible models.

1. The violation of C and T invariances at the level of $10^{-3}$ of strong interactions with conservation of strangeness and parity.[1] The symbol used is $MS^{+}_{+}$ (MS stands for millistrong, the upper plus for conservation of parity, the lower plus for conservation of strangeness).

2. Violation of C and T invariances in electromagnetic interactions.[2] The symbol used is $E^{+}_{+}$.

3. The violation of CP and T at the level of $10^{-3}$ of weak interactions.[3] In this case the existing data definitely point to the existence of the interaction $MW^{-}_{-}$, and the existence of the three remaining combinations $MW^{+}_{-}$, $MW^{-}_{+}$, $MW^{+}_{+}$ can for the time being only be hypothesized.

4. The violation of CP and T in weak electromagnetic interactions.[4,5] As in the previous case the existence, at this time, of the interaction $EM^{-}$ is unavoidable, the other possibilities $EW^{-}_{+}$, $EW^{+}_{-}$, $EW^{+}_{+}$ are hypothetical.

5. Superweak interaction with change in strangeness by 2 (Wolfenstein's model)[6]. The symbol used is SW.

The existing experimental data are reported in detail in other places and I shall only give here data on the parameters of the $K^0\overline{K}^0$ system (in conventional notation)*:

$$|\eta_{+-}| = (1.98 \pm 0.02)\cdot 10^{-3}, \quad |\eta_{00}| = (3.9 \pm 0.3)\cdot 10^{-3},$$
$$\Phi_{+-} = 60 \pm 15^{\circ}, \quad \operatorname{Re}\varepsilon = (1.1 \pm 0.2)\cdot 10^{-3}.$$

The last figure for Re $\epsilon$ is given under the assumption of CPT invariance. The hypothesis on the violation of CPT invariance is discussed in the report of L. I. Lapidus, for which reason it will not be considered here and in the following we shall suppose the validity of the CPT theorem. The indicated data exclude the possibility of the existence of only a superweak interaction SW, which requires $\eta_{+-} = \eta_{00}$ and $\Phi_{+-} = 45^{\circ}$. At the same time one obtains for the parameters $\epsilon$ and $\epsilon'$ values of the same order of magnitude, which indicates that the two pions in the final state may appear with comparable probabilities in the isotopic spin T = 0 and T = 2 states.

Of great importance for the study of the validity of the models are data on the electric dipole moments of the particles. At this time one has for the neutron $d_n < 3\cdot 10^{-22}$ e · cm[7] and for the electron $d_e \lesssim 3\cdot 10^{-23}$ e · cm*. Violation of the C and T invariances in the electromagnetic interaction $E^{+}_{+}$ would lead to the existence of $d_n \sim 10^{-20}$ e · cm. In making this estimate it is supposed that a weak parity-violating interaction between nucleons exists. This assumption has been proven recently in experiments on nuclear transitions.[9] Consequently, the smallness of $d_n$ contradicts the existence of the interaction $E^{+}_{+}$ with isotopic selection rules $\Delta T = 0$ or 1 (except for accidental suppressions). Moreover, the absence of asymmetry in the decay $\eta \rightarrow \pi^{+}\pi^{-}\pi^{0}$[10] testifies that the admixture of T = 2 in the final state of the 3-pion system is here small, which excludes violation of C with $\Delta T = 1$, 2, or 3. Consequently, the existing data allow the interaction $E^{+}_{+}$ with $\Delta T = 4$ and higher. However, such a selection rule combined with the $\Delta T = \frac{1}{2}$ rule in weak interactions forces the interaction in the decay $K_L \rightarrow 2\pi$ to yield the $2\pi$ system in the state T = 2 only, in contradiction with experimental data. We may therefore conclude that the experimental data in no way indicate an electromagnetic violation.

In this fashion the existing data reduce the five possibilities to, essentially, three: MS, MW, EW. For the first possibility, MS, the accuracy of conservation of $T \sim 10^{-3}$, achieved in experiments with nuclei, is not as yet sufficient since one cannot exclude the possibility that this interaction increases with energy (like, for example, the conventional weak interaction) and therefore in addition to the smallness $10^{-3}$ there may enter into nuclear effects the smallness $(m_{\pi}/M_{p})$ (as is the case with weak interactions). The fact that in the decay $K_L \rightarrow 2\pi$ the selection rule $\Delta T = \frac{1}{2}$ is not satisfied, does not necessarily testify against the MS interaction with conservation of isotopic spin, since it is possible that the selection rule $\Delta T = \frac{1}{2}$ has its origin in the structure of conventional strong interactions, while the unknown interaction perhaps does not lead to a strengthening of $\Delta T = \frac{1}{2}$. It is thus most important to increase the accuracy in the search for effects due to C- and T-invariance violation both at high energies ($p\overline{p}$ annihilation, pp scattering, etc.) and in nuclear physics.

Let us pass to a discussion of the milliweak interaction MW. There are many possibilities in this version. At this time one may assert the existence of only the $MW^{-}_{-}$ interaction among hadrons. We do not know, how-

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*We discuss below the effects of a possible change in these numbers.

*The figure $d_e \leqslant (1.7 \pm 0.5)\cdot 10^{-23}$ e · cm is given in [8].

ever, whether the interactions MW$^-_+$, MW$^+_-$, MW$^+_+$ operate among hadrons.* Interactions without change in strangeness will contribute to the electric dipole moments of the neutron $d_n$. One has for the neutron $d_n \sim 10^{-23}$–$10^{-24}$ e · cm if MW$_+$ exists. The interaction MW$^+_-$ with parity conservation but strangeness violation may be studied in the processes $K \to 3\pi$. *If such an interaction does not exist then the partial probabilities* for the decays $K^+ \to 2\pi^+\pi^-$ and $K^- \to 2\pi^-\pi^+$ should be equal, and the fraction of the decay $K_S \to 3\pi^0$ should equal $|\epsilon|^2 \times 4.2 \times 10^{-4}$. Both interactions MW$^{+-}_-$ may be studied in nonleptonic decays of hyperons with the desired accuracy $10^{-3}$. The important effect of MW$^-_-$—the possibility of noncoincidence of the decay spectra $K^+ \to \pi^+\pi^0\gamma$ with accuracy $10^{-2}$[11] is discussed in the report of A. T. Filippov.

It follows from the data on the decay $K_L \to 2\pi$ that the interaction MW$^-_-$ may have the isotopic spin selection rules $\Delta T = 1/2$, $3/2$, or $5/2$, with necessarily one of the *transitions* $\Delta T = 3/2$, *or* $5/2$ being *present*. In experiments comparing the probabilities for the decays $K^\pm \to \pi^\pm\pi^+\pi^-$ one may determine whether the interaction MW$^+_-$ contains terms with $\Delta T = 5/2$, since in that case $R = w_+ - w_-/w_+ + w_- \sim 10^{-3}$, whereas for $R \sim 10^{-5}$ $\Delta T = 1/2$ or $3/2$.[12]

The next stage in extending the sphere of action of the milliweak interaction consists in allowing violation of CP and T also in interactions with participation of leptons under the assumption that the leptonic current keeps its V–A form. This interaction may be combined with the usual weak interaction into a single interaction of the current × current *form*:

$$\mathscr{L}_{\text{int}} = J^{+\alpha} j^\alpha + \text{h.c.}, \tag{1}$$

where $j^\alpha$ is the conventional leptonic current, and $J^\alpha$ is the sum of the conventional weak hadronic current plus the milliweak current violating CP. The product $J^{+\alpha} j^\alpha$ will give in this case a hadron-hadron interaction that violates CP invariance as discussed above, containing, generally speaking, terms conserving and violating the P parity simultaneously. In the matrix elements for leptonic decays the interaction (1) will give rise to the appearance of a small phase ($\sim 10^{-3}$) for the decay form factors, which will be responsible for the effects due to the nonconservation of CP and T invariances. Among the effects to which such an interaction would give rise one should note a difference in the phases between A and V in the $\beta$ decay of the neutron, where at this time one has the accuracy 1.6° (compare the report of Erozolimskiĭ), as well as perpendicular polarization in the decays $K_L \to \pi^\pm\mu^\mp\nu$, $K^\pm \to \pi^0\mu^\pm\nu$, with the latter process being preferred since it has no final state interactions. One needs an accuracy here of $10^{-3}$, whereas in the first decay an accuracy of several percent has been achieved, and for the second no experiments have been carried out. Let us also note the inequality ($\sim 10^{-3}$) of total probabilities and decay spectra $K^\pm \to e^\pm\nu\pi^+\pi^-$[13].

*It has been proposed in some papers that along with* the charged currents (Eq. (1)) there exist in the CP-odd interaction also neutral currents[14], for example $(\bar{\mu}\mu)$, $(\bar{e}e)$, and one should add to Eq. (1) the term

$$J_0^\alpha j_0^\alpha,$$

where $J_0$ does not contain terms of the order of conventional weak interactions, nor does it contain terms for milliweak currents that conserve CP since this would be in contradiction with experiment. In connection with this hypothesis of great interest are the searches for the decay $K_S \to \mu^+\mu^-$, $K^\pm \to \pi^\pm\mu^+\mu^-$, $K^\pm \to \pi^\pm e^+e^-$, for whose *probability the present upper limit is* $\sim 10^{-6}$, which is not in contradiction with the existence of milliweak neutral currents. Of particular interest is the decay $K^\pm \to \pi^\pm\mu^+\mu^-$, since if neutral currents exist then this decay proceeds according to two competing mechanisms: with the exchange of a photon (amplitude of order $\alpha G \sim 10^{-3} G$) and with violation of CP (amplitude of order $10^{-3} G$ also). As a consequence of interference of these two amplitudes a large T-odd correlation may arise, for example, of the form $\sigma_1 \times \sigma_2 \cdot p$ where $\sigma_1$, and $\sigma_2$ are the polarizations of the positive and negative muons.

Returning to charged currents, we note the important *problem*: Is the $\Delta S = \Delta Q$ rule *preserved in the* interaction under discussion? This question is studied by investigating the time dependence of the decays $K^0, \bar{K}^0 \to \pi^\pm l^\mp \nu$. The accuracy at this time is not sufficient: for the ratio X of the amplitudes with $\Delta S = -\Delta Q$ and $\Delta S = \Delta Q$ one obtains the following quantity: $X = (0.26 \pm 0.11)\, e^{i(50 \pm {}^{25°}_{27°})}$.[15]

When we assumed in Eq. (1) that the nonconservation of CP invariance is contained only in the hadronic current we have given up the idea of universality. If on the other hand one attempts to construct a milliweak interaction on the pattern of a universal weak interaction then it becomes natural to introduce also a leptonic CP-odd current. If one supposes that there exists only *such charged currents then one may combine them with* the weak currents and write the weak and the milliweak interaction in one formula

$$\mathscr{L}_{\text{int}} = \frac{G}{\sqrt{2}} \{(J^{+\alpha} + J_M^{+\alpha} + j^{+\alpha} + j_M^\alpha)(J^\alpha + J_M^\alpha + j^\alpha + j_M^\alpha), \tag{2}$$

where the subscript M denotes the milliweak CP-odd interaction. Let us see now what additions can be made to the leptonic current, which is considered first to avoid complications due to strong interactions. The weak current $j^\alpha$ has the form

$$j^\alpha = \bar{e}\gamma^\alpha (1 + \gamma_5)\nu + \bar{\mu}\gamma^\alpha (1 + \gamma_5)\nu.$$

The first thing that can be done is to introduce a phase difference $\varphi \sim 10^{-3}$ between V and A in this current. This will give rise to the neutrino not being strictly two-component and makes it possible for the neutrino to develop a mass. We do not know how to calculate this mass therefore we do not know whether this is in con-

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*There exist models in which the absence of the interaction MW$^+_-$ is quite natural. If one introduces CP nonconservation by assigning a phase difference to A and V in the currents, then the hadron-hadron interaction Lagrangian has the form

$$\mathscr{L}_{\text{int}} = [(V + e^{i\xi}A) + (V' + e^{i\eta}A')]\,[(V^+ + e^{-i\xi}A^+) + (V'^+ + e^{-i\eta}A'^+)],$$

where the prime indicates strange currents ($\xi, \eta \sim 10^{-3}$). It is easily seen that for $\xi = \eta$ there is no nonconservation of CP in the terms VV$'^+$ and AA$'^+$, it only being present in the terms VA$'^+$ which do not conserve parity. On the other hand, the condition $\xi = -\eta$ gives nonconservation of CP with parity conservation, whereas the parity nonconserving part simply acquires a common phase.

tradiction with experimental limits. A more decisive effect consists in the absence of complete polarization of the muon along the direction of motion in the decays $\pi \rightarrow \mu\nu$ and $K \rightarrow \mu\nu$, however this effect will be here of order $\varphi^2$, i.e. $10^{-6}$.

Naturally, such a change will give rise to the appearance in the $\mu$ decay of a T-odd correlation $\sigma_\mu \times \sigma \cdot p$ of order $10^{-3}$, and also to effects in leptonic decays of hadrons, which were already discussed. If we remain within the framework of vector currents without derivatives then there are no other possibilities for the introduction of CP nonconservation. Many more possibilities arise if one uses derivatives in the construction of the current. If in addition we impose the condition of a two-component neutrino and limit ourselves to one differentiation then the general form of the additions to the current will be

$$j_M^\alpha = \frac{10^{-3}}{M}\left(a_1\,\partial_\alpha\bar{e}\,(1+\gamma_5)\,\nu + a_2\bar{e}\,(1+\gamma_5)\,\partial_\alpha\nu + a_3\,\partial_\beta\bar{e}\gamma_\beta\gamma_\alpha\,(1+\gamma_5)\,\nu + a_4\bar{e}\gamma_\alpha\gamma_\beta\,(1+\gamma_5)\,\partial_\beta\nu\right), \tag{3}$$

and analogous terms for the muon ($a_i$ is of order of unity, M is a mass introduced from dimensional considerations and equal in order of magnitude to the nucleon mass). The first thing to which one should call attention is the fact that the quantity $10^{-3}/M$ is close in magnitude to $\sqrt{G} \sim 3 \times 10^{-3}/M$. It is therefore deceptive to suppose that in this case the smallness is determined by precisely this known constant, with the milliweak interaction becoming strong at the same energies as the weak, i.e. for $E \sim 300$ GeV. It is of course possible that this coincidence is accidental. The current (3), multiplied by the hadronic current, will give rise to the same correlations as violation of CP and T in interactions of the form (1). It is therefore a most complicated question to decide whether the T-odd correlation is due in the, say, decay $K^+ \rightarrow \pi^0\mu^+\nu$ to the interaction (1) or (3). In a pure form the effect of the current (3) may appear in the decay of the muon where we obtain for the order of magnitude of the correlation $\sigma_\mu \times \sigma_e \cdot p$ the rather small number $\sim m_\mu/M \times 10^{-3} \sim 10^{-4}$. However, a class of processes exists where the change of leptonic currents of the form (3) may appear rather decisively—these are processes which are suppressed as a consequence of the V—A structure of the currents in the usual weak interaction. It is well known that in the conventional theory of weak interactions the decays $\pi \rightarrow e\nu$, $K \rightarrow e\nu$, are strongly suppressed, the ratio of their probabilities to those of the probabilities for the main decays $\pi \rightarrow \mu\nu$, $K \rightarrow \mu\nu$ being a very well defined number depending on the masses of the particles and given by

$$\left(\frac{m_e}{m_\mu}\right)^2 \frac{\left(1-\left(\frac{m_e}{\mu}\right)^2\right)^2}{\left(1-\left(\frac{m_\mu}{\mu}\right)^2\right)^2},$$

where $\mu$ is the mass of the pion or K meson. The current (3) gives rise to the same decays without additional suppression and the above indicated ratio is modified by the factor

$$1+(a_1+a_2)^2\,\frac{10^{-6}}{M^2}\,\frac{\mu^4}{m_e^2};$$

for $a_1 + a_2 \sim 1$ this addition amounts to $1.5 \times 10^{-3}$ for the decay $\pi \rightarrow e\nu$, and to $\sim 30\%$ for the decay $K \rightarrow e\nu$. The contribution to the decay of the K meson is large due to its large mass, with the fraction of the CP-odd amplitude for the K meson approximately ten times bigger than for the pion. The indicated estimates are not in contradiction with experimental data, however the observation of a similar effect could not be used as proof of the existence of precisely the current (3) as the CP-noninvariant interaction. Direct effects due to violation of T invariance may also be observed in the decays $K \rightarrow e\nu\gamma$, $\pi \rightarrow e\nu\gamma$. In these decays the bremsstrahlung terms are suppressed for the same reason as the decays K, $\pi \rightarrow e\nu$, and the structural radiation, at least in the case of the decay $\pi \rightarrow e\nu$, is small which follows from estimates based on the CVC hypothesis,[16] and also from experiment. In comparison with these small amplitudes the CP-odd amplitude for bremsstrahlung due to Eq. (3), turns out to be of the same order and therefore may give rise to substantial T-odd correlations, connected both with the polarization of the photon and the polarization of the electron. The effect involving the photon polarization (the term $n_1\epsilon \times n_2\epsilon$, where $\epsilon$ is the photon polarization and $n_1$ and $n_2$ are two directions perpendicular to each other and to the photon momentum) may reach for the K decay several percent (for the $\pi$ decay it is ten times smaller), and the transverse polarization of the electron with CVC taken into account may amount to several percent for the pion and 10—20% for the K meson. In this manner the decays K, $\pi \rightarrow e\nu\gamma$ provide one of several possibilities for the study of the structure of leptonic currents, although, naturally, in view of the rarity of such processes the experiments are rather difficult. It should be emphasized that as long as we consider experiments connected with violation of CP and T in hadronic currents we cannot conclude from the results of the experiments, even if positive, that the violation occurs in milliweak or millistrong interactions. For this reason experiments with leptons are of great importance.

Let us pass to a short discussion of electromagnetic-weak interactions EW[4,5]. One may imagine the violation of CP and T invariances in EW in a variety of ways, which is easiest to illustrate on the example of a particle with spin ½. The first possibility consists in the introduction of a CP-violating interaction with constant ~ eG in the transition of one particle into another with the emission of a photon.[4] In that case in order to explain the basic effect one requires the existence of the interaction $EW_{1-}^{-}$ with strangeness nonconservation (subscript) and parity nonconservation (superscript). For such an interaction the constant eG is fully determined from dimensional considerations without the introduction of additional masses. The second possibility consists of the emission of the photon with nonconservation of CP straight from the middle of the 4-fermion interaction with a coupling constant eG also. The hypothesis assigning the nonconservation of CP and T to the existence of an electric dipole moment for the hypothetical intermediate W boson belongs also to this second possibility, $EW_2$.[5] Estimates of the dipole moment of the neutron utilizing the latter mechanism give a quantity $10^{-20}$—$10^{-21}$ e · cm, which is already in contradiction with experimental data. For the general $EW_2$ interaction the experiment also requires for the time being only the existence of the component $EW_{2-}^{-}$. It is easy to see that as long as we deal with only hadronic weak and weak radiative decays the consequences of $EW_1$ and $EW_2$ coincide. In particular, the existence of $EW^{\pm}$ would lead to the forbidden (to lowest order in the electromagnetic interaction) by CP invariance decay $K_L \to \pi^0 e^+ e^-$ ($\mu^+\mu^-$) with the probability ~ $10^{-6}$ $W_L$. The $EW^{\pm}$ interaction gives rise, as a rule, to large effects in weak-electromagnetic decays, where it competes with the conventional CP-even mechanism, equal to it in order of magnitude. In particular there should be a strong difference in the probabilities for the decays $K^+ \to \pi^+\pi^0\gamma$ and $K^- \to \pi^-\pi^0\gamma$. Similar effects are discussed in the report of A. T. Filippov. The $EW_1^{\pm}$ interaction could give rise to electric dipole moments for particles if diagonal transitions, for example $nn\gamma$, exist. The neutron data exclude the possibility of a large value for such a diagonal transition for it.

As regards processes involving leptons here the predictions of $EW_1$ and $EW_2$ differ. $EW_1$ does not predict noticeable effects of nonconservation of CP and T in the decays with the emission of leptonic pairs, even including the emission of a photon, since in addition to the weak constant in the electromagnetic-weak vertex one must add to the amplitude one more constant, G in the leptonic vertex. At the same time $EW_2$ predicts large effects in the structural part of the leptonic weak-radiative decays and effects ~ $10^{-3}$ for nonradiative transitions.

In conclusion let us note that the data on weak radiative processes are so few that no conclusions on the validity of this mechanism can be reached. It is therefore appropriate to once more emphasize the importance of, for example, the decays $K^{\pm} \to \pi^{\pm}\pi^0\gamma$, which could give important information.

It remains to discuss the model of the superweak interaction. Although the published data on the decay $K_L \to 2\pi^0$ definitely exclude this possibility, a final conclusion on the probability of the decay $K_L \to 2\pi^0$ cannot be made and it is not out of the question that more precise data will give agreement with the SW model. However, even if the parameters of the decay $K_L \to 2\pi$ should satisfy the requirement of the SW model, which gives rise to no effect anywhere, except for the $K^0\bar{K}^0$ system, there exists also other models for violation of CP which give rise to the same parameters. For example, the milliweak interaction, which does not violate the $T = \frac{1}{2}$ rule; the milliweak interaction with $T = \frac{1}{2}$; the milliweak interaction with parity conservation; the electromagnetic-weak interaction with conservation of parity. One should particularly consider the latter two possibilities. Parity conservation in these interactions ensures absence of a direct transition $K_L \to 2\pi^0$, and the decay proceeds only through $K_L \to K_S$, as in the SW model. In those processes where parity is conserved, there will be, in contrast to SW, effects due to nonconservation of CP. For example, the probability for the decay $K_S \to 3\pi^0$ will be different from that predicted by SW. Thus, even if the development of events should lead us to the equality $\eta_{+-} = \eta_{00}$, there still remains a wide field of activity for searching for other effects.

## DISCUSSION

DISCUSSION

**B. Pontecorvo:**

What are the experimental limits for the possible size of the relative phase $\varphi$ of the vector and axial currents in the lepton-lepton interactions?

**B. A. Arbuzov:**

The limit $\varphi < 16°$ follows from $\mu$ decay.

**F. L. Shapiro:**

What are the predictions of different models for the electric dipole moment of leptons?

**B. A. Arbuzov:**

The MS, E and SW versions (in the notation used in the report) give very small values for the dipole moment of the electron (e.d.m.) in comparison with the quantity $eGm_e \sim 10^{-23}$ (e, G being the constants of the electromagnetic and weak interactions, and $m_e$ being the electron mass). In the weak-electromagnetic version an e.d.m. of ~ $10^{-23}$ e · cm is possible for the electron. In certain versions of the milliweak interaction it is also possible to obtain an appreciable e.d.m. for the electron ~ $10^{-23}$–$10^{-25}$ e · cm. It should be, however, kept in mind that the last estimate is obtained for a very large (300 GeV) cutoff momentum in the divergent integrals, in terms of which the e.d.m. is expressed.

**T. Miller:**

What is the estimate of the electric dipole moment of the neutron in the millistrong interaction?

**B. A. Arbuzov:**

The order of magnitude here is the same as in the milliweak interaction: $d_n \sim 10^{-23}$–$10^{-24}$ e · cm.

**E. N. Lipmanov:**

It seems to me that the decay $K_S \to \mu^+\mu^-$ is more critical from the point of view of a test for the theory

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than it was noted in the report. If one were to study simultaneously the decay $K_S \rightarrow e^+e^-$, then the existence of the channel $K_S \rightarrow \mu^+\mu^-$ and the absence of the channel $K_S \rightarrow e^+e^-$ would indicate the vector or axial variant and thus serve as proof of CP violation.

**B. A. Arbuzov:**

This assertion is correct under the additional assumption of symmetry between the muon and the electron.

**G. Marks:**

In my opinion the present day experimental data exclude the possibility of violation of C and T invariances in millistrong interactions with $\Delta T = 0$, since in the opposite case the rule $\Delta T = \frac{1}{2}$ would be satisfied in weak interactions with violation of CP invariance. The fact that the interaction constant of the millistrong interaction is of the order $10^{-3}$ makes it possible to discuss this interaction in perturbation theory and therefore the millistrong interaction cannot change selection rules.

**B. A. Arbuzov:**

I think that it is not possible to exclude at this time the MS interaction with $\Delta T = 0$. The point is that we do not understand the nature of the $\Delta T = \frac{1}{2}$ rule in weak interactions. There exist two points of view. The first, that the $\Delta T = \frac{1}{2}$ rule is contained in the very structure of the weak interactions (in which case neutral currents must exist), and second that in the initial Hamiltonian for the weak interactions there exist transitions with both $\Delta T = \frac{1}{2}$ and $\Delta T = \frac{3}{2}$. If, for example, the Hamiltonian has the form of the product of charged currents then the $\Delta T = \frac{1}{2}$ rule is obtained as a result of an enhancement of the transitions with $\Delta T = \frac{1}{2}$ by strong interactions. In the first case, indeed, the possibility of the existence of MS interaction with $\Delta T = 0$ is excluded. In the second case there are no particular reasons to believe that the combination of the strong and MS interactions necessarily gives rise to an enhancement of the transitions with $\Delta T = \frac{1}{2}$ with CP nonconservation, since the current structure of the interaction MS × W may substantially differ from the current structure of the conventional weak interactions.

**B. Pontecorvo:**

I would like to make two remarks. The first refers to the milliweak interaction and is a milli remark: It is very short. The second refers to the superweak interaction, but is nevertheless a mega remark (i.e. it is very long).

1. The milliweak interaction may give rise to a rather large dipole electric (and magnetic) moment of the neutrino $d_\nu$: $d_\nu \leq G10^{-3}\Lambda^2(1/\Lambda)e \approx 10^{-20}\,e \cdot \mathrm{cm}$, where $\Lambda$ ($\lesssim 100$ GeV) is the cut-off parameter of the weak interaction.

2. The extreme smallness of the constant f of the superweak interaction of Wolfenstein ($f \sim 10^{-9}$ G, where $G = 10^{-5}/M_p^2$) makes difficult the observation of processes due to the superweak interaction, except for processes with the participation of $K^0$ mesons.

It is natural to ask: Can one observe, and in what manner, other manifestations of this interaction? To put it differently: Can one at all observe, and in what manner, other processes which proceed with a constant a million times smaller than the weak interaction constant? In the latter form the question is no longer referring directly to the Wolfenstein interaction, and in what follows the notation for the constant f, as well as its size $\sim 10^{-9}$ G are taken for illustration.

The superweakness of the interaction being considered leads one to think that its manifestation should be looked for in processes similar to those produced by the weak interaction of second order in G. The often encountered assertion that the Wolfenstein interaction of first order cannot compete with the weak interaction of second order is not necessarily correct. If in the processes under consideration only hadrons participate then the effective masses and cut-off parameters are of order $M_p$, so that indeed $fM_p^2 \ll G^2M_p^4$. However, the dimensionality of the constants f and G gives rise to the fact that the superweak interaction of first order in f can fully compete with the weak interaction of second order in G, for example in the cases when the processes involve leptons (only real ones) with low energy. In this connection it is natural to compare the well understood theoretically process of neutrino double $\beta$ decay (effectively of order $G^2$) with the hypothetical process of a neutrino-less double $\beta$-decay caused by an interaction à la Wolfenstein.

Below we consider the following working hypothesis: the neutrinoless double $\beta$ decay is caused by a certain superweak interaction of first order in f with $\Delta L = 2$, where L is the lepton number. We are dealing here with the direct interaction of hadrons with a doubly charged leptonic current without the participation of a virtual neutrino (Fig. 1a and b). It is true that such an interaction is exotic. However, the interaction $\Delta S = 2$ is also exotic, as well as the interaction with $\Delta L = 2$, which is usually invoked if one postulates the existence of a neutrinoless double $\beta$-decay (see "the conventional" diagram for this event in Fig. 2).

In the diagrams Fig. 1a and b we show effects due to virtual pions, which make possible the decay $Z \rightarrow (Z+2) + e^- + e^-$, caused by the interaction f.

It is seen that the interaction with the constant f of the order $10^{-9}$ G or even smaller could, in principle, give rise to a neutrinoless double $\beta$ decay with a probability in excess of the probability for the neutrino double $\beta$ decay.

Therefore the search for the neutrinoless double $\beta$ decay could help to obtain information on the possible superweak interactions.

Let us discuss now the radio-chemical experiments of Takaoki and Ogaty on the double $\beta$ decay, in which an excess over the normal isotopic distribution of isotopes of Xe in old minerals of Te of known age was determined. Other experimental set-ups with counters and spark chambers, in contrast to the radio-chemical experiments, are able, in principle, to distinguish the neutrino process from the neutrinoless, however, they are less sensitive, particularly in cases of interest from our point of view, when the energy liberated in the double $\beta$-decay process is very small ($\leq 1$ MeV). In experiments on the transformation $Te^{130} \rightarrow Xe^{130}$ the phenomenon of double $\beta$ decay was discovered, with the total probability $W_{e^-e^-}^{Te^{130}} + W_{e^-e^-\nu\bar{\nu}}^{Te^{130}}$ approximately equal to $10^{-21}$ year$^{-1}$ (an obvious notation). Moreover the

Japanese authors report that in old Te minerals a certain excess of $Xe^{128}$ was found. Should such an excess be due to double $\beta$ decay $Te^{128} \rightarrow Xe^{128}$, then the probability $W^{Te^{128}}_{e^-e^-} + W^{Te^{128}}_{e^-e^-\nu\bar{\nu}}$ is equal to $\sim 3 \times 10^{-23}$ $year^{-1}$. The authors lean to the conclusion that the observed by them excess of $Xe^{130}$ is due to neutrino double $\beta$ decay and that the neutrinoless processes in general don't exist. At that the most interesting observation of an excess of $Xe^{128}$ should be due, in the opinion of the authors, to a background, since the indicated probability for the production of $Xe^{128}$ from $Te^{128}$ is at least by three orders of magnitude larger than the theoretical probability for the neutrino double $\beta$ decay, expected for $Te^{128}$, where the energy released in the process is of the order 0.85 MeV.

As a working hypothesis, however, we call attention to the possibility that the transitions $Te^{128} \rightarrow Xe^{128}$ are totally, and the transition $Te^{130} \rightarrow Xe^{130}$ is partially due to the neutrinoless $\beta$ decay. There is then a priori no difficulty with the large magnitude for the probability of the effect in $Te^{128}$: the neutrinoless decay cannot be for the moment calculated for a number of reasons and, in particular, because the constants f (Fig. 1) and f′ (Fig. 2) are unknown. Since the dependence on the energy release $\epsilon$ in the neutrinoless $\beta$ decay $\sim \epsilon^{5\div 6}$ (cf. conventional $\beta$ decay), and in the neutrino double $\beta$ decay $\sim \epsilon^{10}$, the neutrinoless double $\beta$ decay is relatively more probable for $Te^{128}$ than for $Te^{130}$ ($\epsilon$ is equal to 0.85 MeV and 3.0 MeV respectively). On the other hand the absolute probability for the neutrinoless $\beta$ decay should be several hundred times smaller in $Te^{128}$ than in $Te^{130}$, all other conditions being the same. Since however the nuclear matrix elements are only known accurate to two orders, the observed ratio ($W^{Te^{128}}/W^{Te^{130}} \leq 30$) is not in contradiction with anything. An analogous argument is applicable to the latest, first-rate experiment of Wu and collaborators searching for the neutrinoless $\beta$ decay in $Ca^{48}$ ($W^{Ca^{48}}_{e^-e^-} \leq 10^{-21}$ $year^{-1}$). The scheme for the neutrinoless double $\beta$ decay in Fig. 1 is more natural than the conventional interpretation in terms of the diagram of Fig. 2. The latter diagram is of order Gf′, where f′ is the interaction constant which, like the interaction $W_f$, changes the leptonic charge by two units.

It follows from the totality of experiments testing the V—A theory that $f' < 0.02$ G, so that the probability for the neutrinoless decay according to the diagram of Fig. 2 is at least by three orders of magnitude suppressed relative to the calculated probability in the case of parity conservation with maximal violation of the leptonic charge ($f' = G$).

Let us suppose now that indeed the neutrinoless double $\beta$ decay occurs in $Te^{128}$ and other nuclei. Question: How can one verify experimentally whether the neutrinoless decay is due to diagrams of Fig. 1 or Fig. 2?

If the neutrinoless decay proceeds according to the diagram of Fig. 2 then there should occur processes violating lepton conservation of the type $\bar{\nu}_e + n \rightarrow e^- + p$, $\nu_\mu + p \rightarrow n + \mu^+$ with a cross section approximately calculable and, perhaps, accessible to experimental test. These processes, on the other hand, do not occur via the interaction f (cf. Fig. 1), which makes it possible to distinguish in principle, which of the interactions is responsible for the neutrinoless process.

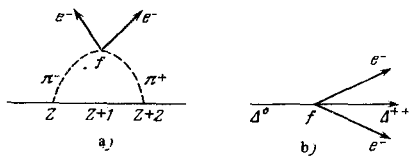

FIG. 1. Possible diagrams for neutrinoless double beta decay caused by the f interaction (Δ stands for the well known isobar with mass of 1240 MeV).

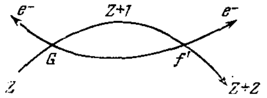

FIG. 2. "Conventional" interpretation of neutrinoless double beta decay.

The interaction f may cause in vacuum the transition pionium $\rightleftarrows$ antipionium ($\pi^+e^- \rightleftarrows \pi^-e^+$) and, perhaps muonium $\rightleftarrows$ antimuonium. However, it is hard to see how one might observe in practice such oscillations due to the extreme smallness of the constant f.

Above the neutrinoless double $\beta$ decay was described as a transition with $\Delta L = 2$, i.e. under the assumption of the existence of a lepton conservation law, which is violated by the f (or f′) interaction. One can, of course, interpret the neutrinoless double $\beta$ decay simply by absence of the leptonic charge (Majorana neutrino with approximate V—A interaction). The two approaches, however, differ physically. The first gives rise to the possibility of oscillations in vacuum between different states of the neutrino (when $m_\nu \neq 0$). In the second approach such oscillations are not possible. Moreover, in the second approach the interaction f may give rise to a neutrinoless double $\beta$ decay even if the neutrino is longitudinal ($m_\nu = 0$).

**F. L. Shapiro:**

I have a question to A. T. Filippov. What can you say about the electric dipole moments of particles?

**A. T. Filippov:**

The size of the electric dipole moment of an elementary particle depends only on the choice of the concrete model for the violation of T invariance, even in the framework of the electromagnetic mechanism of such a violation. Therefore, from just the absence of a dipole moment for the neutron one cannot conclude unambiguously that T-invariance violation is absent from electromagnetic interactions. In the text of the report a model is given for the electromagnetic violation in which the dipole moment of the neutron should be small ($\sim 10^{-22}$—$10^{-23}$ e · cm). From an analysis of this model it follows that the possibility of an electromagnetic violation of the T invariance with $\Delta I = 0$ cannot yet be definitely rejected and the search for such a violation should be continued.

**Yu. G. Abov:**

What can be the size of the T-odd correlation $\mathbf{s} \cdot \mathbf{k}_1 \times \mathbf{k}_2$ in processes with the emission of two photons by a polarized nucleus ($\mathbf{s}$ being the nucleus polarization, $\mathbf{k}_1$ and $\mathbf{k}_2$ being photon momenta)?

**A. T. Filippov:**

It is clear that such correlations may be comparable with the T-even correlations only in the presence of an electromagnetic mechanism for violation of T invariance. However, in that case one may expect a strong dependence of the effect on the energy of the photon and on the extent to which the nucleon emitting the photon is off the mass shell. Two considerations may be mentioned in favor of this assertion. In the first place the abovementioned discussion on the dipole moment of the neutron $d_n$ shows that the smallness of the quantity $d_n$ may be put in agreement with the electromagnetic mechanism by allowing a strong dependence of the T-odd form factors on the momenta and, in particular, supposing that these form factors vanish on the mass shell. In the second place, an analogous conclusion is reached when attempting to explain with the help of the electromagnetic mechanism the size of the probability for the decay $K_L \to 2\pi$. Indeed, it is usually said that for the quantity $\eta_{+-}$ one should obtain something of the order $\eta_{+} \approx \alpha/\pi$, since the exchange of one virtual photon occurs. However, the calculation of various diagrams shows that for $\eta_{+-}$ one obtains a substantially smaller number, if these diagrams converge or if they are cut-off at a sufficiently small limit. Thus, in order to explain at least the order of magnitude of the quantity $\eta_{+-}$ it is necessary to assume a rapid growth of the T-odd electromagnetic interaction with increasing virtual momenta. One may arrive at the same conclusion by considering conventional unitarity relations for the decay $K_L \to 2\pi$. The contribution of real radiative processes $K_L \to 2\gamma/2\pi\gamma$ to $\eta_{+-}$ turns out to be $\lesssim 1\%$. From these general considerations one should choose the most favorable conditions to search for the correlation $\mathbf{s} \cdot \mathbf{k}_1 \times \mathbf{k}_2$, however more precise predictions depend on the concrete models for the electromagnetic violation of T invariance.

Translated by A. M. Bincer