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

539.12.01

PROBLEMS RELATED TO THE VIOLATION OF CP INVARIANCE

L. B. OKUN'

Institute for Theoretical and Experimental Physics, Moscow

Usp. Fiz. Nauk. 95, 402-416 (July, 1968)

THE operations of charge conjugation C, space reflection P, and time reversal T have been under investigation by physicists for about forty years. The interest in these operations has become particularly strong when a violation of CP invariance was discovered four years ago.

Why is it that the violation of CP invariance has provoked so much interest?

Maybe because this is one of the most fundamental problems of contemporary physics, in connection with which have anew arisen the problems of relation between particles and antiparticles, of the mirror symmetry of the world and of the arrow of time.

Maybe because in discovering the violation of CP invariance physicists have encountered a new type of interaction. To the four known interactions—the strong, the electromagnetic, the weak, and the gravitational—a fifth interaction has been added, which violates CP invariance.

It is hard to indicate another fundamental problem which is being as actively pursued from the experimental point of view. Such investigations are now carried out intensively in tens of laboratories all around the world and have gone far beyond the physics of K mesons. In searching for CP violations the decays of η mesons have been subjected to a scrupulous investigation, as well as nuclear reactions, the electromagnetic properties of the neutron and electron, and the decays of hyperons and nuclei. Such investigations have achieved record levels of accuracy, and experiments have been performed which only a few years ago were considered impossible. Unfortunately, the violation of CP invariance was not observed in any other phenomenon but the decay of the neutral K mesons. In this respect what is happening now differs radically from the events of eleven years ago. Then the violation of parity, the discovery of which was prompted by the decays of K^+ mesons into two and three pions, was detected simultaneously practically in all weak decays. Now, already four years have passed since the violation of CP invariance was discovered in the decay of the long-lived neutral K meson: $K_L^0 \rightarrow \pi^+\pi^-$, but still no CP noninvariant effects could be found for particles other than the K^0 mesons.*

On the other hand, considerable progress has been achieved in the investigation of the properties of the K^0 mesons themselves. First of all, the decay mode $K_L^0 \rightarrow \pi^+\pi^-$ has been studied most carefully. Whereas the first paper describing the decay was based on tens of such decays, nowadays the numbers are in the thousands.

It has been established that this decay is indeed caused by a violation of CP invariance, and is not a consequence of some long-range forces, the source of which might be the Earth, the Sun, or the Galaxy. This was established on the basis of the fact that under the action of such forces the ratio of the width of the decay $K_L^0 \rightarrow \pi^+\pi^-$ to the total width of the K_L^0 meson would increase as the square of the energy of the K_L^0 meson. But the experiment shows that this ratio does not depend on the energy.

A series of experiments were realized with the purpose of determining not only the absolute value of the amplitude for the decay $K_L^0 \rightarrow \pi^+\pi^-$, but also of its phase, or more precisely of the phase of this amplitude relative to the amplitude of the CP permitted decay $K_S^0 \rightarrow \pi^+\pi^-$. It is obvious that this phase can be measured only if one observes phenomena caused by the interference of these two amplitudes. Such phenomena have been observed, but their interpretation still involves large errors.

Extremely difficult experiments on the detection of the decay $K_L^0 \rightarrow 2\pi^0$ and its rate have been realized. It is easy to grasp the degree of difficulty of these experiments, if one considers that the products of this decay (four photons) are neutral, and the detection of this decay must be done on the background of the CP permitted mode $K_L^0 \rightarrow 3\pi^0$, which is by two orders of magnitude more probable. It is therefore not astonishing that the experimental values of the rate of this decay have been subject to perpetual change in the past year.

Finally, the phenomenon of charge asymmetry was observed in leptonic decays of the K_L^0 meson. The existence of this asymmetry clearly demonstrates the fact that in nature positive and negative charges do not have the same rights, a fact which is an unavoidable consequence of CP violation. It turned out that in vacuum the neutral K_L^0 meson yields more decays into $\pi^-e^+\nu$ than into $\pi^+e^-\bar{\nu}$. The same was also observed for decays into $\pi^-\mu^+\nu$ and $\pi^+\mu^-\bar{\nu}$. In the same manner as other effects which are odd under CP (henceforth—CP-odd) this charge asymmetry is extremely small ($\sim 10^{-3}$), and the latest experiment required the registration of 17 million decays in order to measure the effect.

The main purpose of numerous experiments is to find a mechanism for the violation of CP invariance, i.e., to determine the properties of the interaction which is responsible for this violation.

If one uses nuclear units, with $\hbar = c = m = 1$, where m is the pion mass, then the strong interaction coupling constant will be of order unity, the electromagnetic coupling constant is $\sim 10^{-1}$, the weak coupling constant

---

*We remind the reader that nonconservation of parity was a consequence of the fact that the K^+ meson could decay both into $\pi^+\pi^0$ and $2\pi^+\pi^-$, and the pions have negative P-parity, so that the system 2π is even and 3π is odd. Similarly from the fact that the K_L^0 meson can decay into a 3π system having negative CP-parity and into a system of 2π having positive CP-parity, one can infer that CP-parity is not conserved.

is $\sim 10^{-5}$ and the gravitational constant is $\sim 10^{-40}$. What is the order of magnitude of the new, CP-violating, interaction? So far we still have no answer to this question. The possible values of this constant are spread from a magnitude of the order of 10^{-2} to 10^{-16}.

The problem whether the violation of CP-invariance is a manifestation of a "new" interaction or the manifestation of as yet unknown properties of one of the "old" interactions is in a certain sense a semantic one. Thus it might happen that the coupling constant and the particles participating in that coupling are the same for the "new" CP-violating interaction as for one of the "old" interactions. In particular, the hypothesis that CP-invariance is violated in the electromagnetic interaction has been discussed in detail in the literature. Specially designed experiments have not confirmed this hypothesis.

It is obvious that the smaller the coupling constant, the less accessible will the corresponding interaction be to experimental investigation. The least favorable from the point of view of possible experimental consequences is the so-called superweak interaction, with a coupling constant of the order 10^{-15}–10^{-16}. This interaction is capable of yielding observable effects only in K^0-meson decays and nowhere else.

It is natural to ask the question: if the coupling constant is so small, how come the interaction is still observable, and manifests itself in the decays of K^0-mesons? It would seem that such an interaction would yield rates by twenty orders of magnitude smaller than those produced by the weak interaction. The answer to this question resides in the fact that in the case of neutral K mesons we deal with two closely spaced states with opposite CP: $K_1^0 = (K^0 + \tilde{K}^0)/2^{1/2}$, $K_2^0 = (K^0 - \tilde{K}^0)/2^{1/2}$. The mass difference of these two states is of the order 10^{-5} eV. As a result of this even the superweak interaction is capable of mixing these states somewhat and to lead to observable effects of violation of CP-parity. This phenomenon is completely unique: we do not know of another example of such a degeneracy.

One can show that one of the consequences of the superweak interaction is the branching ratio:

$$\frac{W(K_L^0 \longrightarrow \pi^+\pi^-)}{W(K_L^0 \longrightarrow 2\pi^0)} = \frac{W(K_S^0 \longrightarrow \pi^+\pi^-)}{W(K_S^0 \longrightarrow 2\pi^0)}.$$

The right-hand side of this is more or less well known from experiments and is close to 2. The left-hand side is known only with large uncertainty. Thus new and more precise data on K^0-decays are extremely important.

If CP-invariance is violated, it is obvious that time-reversal invariance should also be violated. However, there is no direct experimental confirmation of violation of T-invariance.

As we know, the electric dipole moments of particles vanish as a consequence of T-invariance. This assertion is easy to understand if one takes into account the fact that the only distinguished direction in space for a particle at rest is the direction of its intrinsic angular momentum, spin. Therefore the dipole moment of a particle (if the particle has one) must be directed along its spin. But the dipole moment **d** is a polar vector ($\mathbf{d} \sim e\mathbf{r}$) which does not change sign under time-reversal, whereas the angular momentum **J** is an axial vector ($\mathbf{J} \sim \mathbf{r} \times \mathbf{p}$) which changes sign under the substitution $t \rightarrow -t$. Therefore the vector **d** can be directed along **J** only if both space inversion (P) and time reversal (T) are violated.

Large efforts have been devoted recently towards a detection of an electric dipole moment of the neutron. Such a quantity was not observed, but the accuracy attained allows us to assert that the electric dipole moment of the neutron is at least by eight orders smaller than the magnetic moment.

Note that a violation of T-invariance must lead to a violation of the principal of detailed balance: the matrix elements of a direct and inverse reaction need not in general be equal to each other. In principle this should manifest itself on the kinetics of macroscopic processes, but it should not of course modify the form of static distributions.

Approximately forty years ago the idea of charge symmetry of physical equations seemed strange even to the founders of relativistic quantum mechanics (cf., e.g., the 1932 version of Pauli's "Handbuch" article). However the entire structure of the fundamental equations of physics required such a symmetry, and the subsequent discovery of antiparticles was a brilliant confirmation of this fact. Does the breakdown of P, C, and CP signify that the concept of such a symmetry was completely false? No, it does not, as long as CPT-invariance remains inviolate.

Consider a process, e.g., the decay $K_L^0 \rightarrow \pi^-\mu^+\nu$ and let us take its mirror image. Owing to violation of P-invariance we see in the mirror a process which does not exist in Nature. Let us exchange in the initial process all particles by their antiparticles; owing to C-violation this process does also not exist in Nature. Finally, let us reverse the signs of all momenta and spins in the initial process; if T-invariance is violated we should again obtain a physically unrealizable process. Unphysical processes will also be obtained by taking the pair products CP, PT and TC. If however one effects the transformations P, C, and T together any physical process is again taken into a process which can be realized in Nature. This is what is meant by CPT-invariance.

Strictly speaking, CPT-invariance has not yet been tested directly. However few, if any, among the theoretical physicists doubt the survival of CPT-invariance. The reason for this is that it is easy to conceive models of violation of CP- and T-invariance. For this it suffices to replace some real constant in the interaction Lagrangian by a complex one. The whole formalism of the theory remains unchanged. But no one has succeeded in writing a reasonable CPT-noninvariant Lagrangian. Should it turn out that CPT-invariance is violated this would shake the very foundations on which present-day physics is built.

It should be clear from the above that theoretical physicists have accepted CP-violation and do not consider CP-violation and do not consider CP-violating Lagrangians as having vices. Then why did the majority of physicists consider CP-invariance immovable until 1964? What made it difficult to abandon this principle earlier? Sometimes this difficulty is formulated as a problem of choice. Roughly speaking, there is the following question: how does Nature choose among the phases $+i\varphi$ and $-i\varphi$ in the complex constant of an interaction Lagrangian? And since no one knew an answer to this query, one drew the conclusion that the interaction constant must be real, i.e., $\varphi = 0$, and that consequently, CP-invariance could not be violated.

Essentially the same objection was raised at its time against violation of P-invariance: how can Nature choose among the two possible signs in a pseudoscalar term in the interaction Lagrangian? The answer to this latter problem, proposed at the end of 1956 was that Nature does not have to make that choice. According to the hypothesis advanced by L. D. Landau "combined parity" (i.e., CP-parity) of a particle is conserved, and hence if a particle exhibits a left-hand screw (helicity) its antiparticle will be right-handed. Thus the right-left symmetry and particle-antiparticle symmetry are saved, although for particles alone (without antiparticles) there is no longer any mirror symmetry.

Let us imagine for a moment that in 1956 in place of the effects of P- and C-violation which were actually discovered, one had discovered some effects of T- and C-violation, e.g., the charge asymmetry in $K_{\mu 3}$ decays of the long-lived neutral kaon, which we mentioned above. The existence of such an effect means that somewhere in the total Lagrangian there is a term with a complex constant. However in this case the problem of choosing the phase of this constant would not have arisen, since this choice is purely a matter of convention, and depends on what one chooses to call particle and what antiparticle. Changing the direction of the arrow of time (or interchanging the initial and final states of some reaction) and replacing all particles by their antiparticles, one is led to a process which has an amplitude exactly equal to the amplitude of the initial process.

Thus one might say that in a CT-invariant, but C- and T-noninvariant microcosm, both directions of time would be equivalent, in the same sense in which a CP-invariant, but P- and C-noninvariant world the right-handed and left-handed triples of cartesian coordinate unit vectors are equivalent. In both examples we could conserve the geometric symmetries by enlarging their content and interpretation, utilizing for this purpose an additional symmetry which is known to exist in Nature..

But one is not allowed to use C twice, in order to "mend" both P and T. As a result of this, if CP invariance is violated, the particle-antiparticle degeneracy does not suffice to save both T- and P-symmetry. Using a particle-antiparticle transformation we are able to conserve only PT-symmetry. Thus in place of two geometrical symmetries we are left with only one, namely CPT. We were forced to combine two geometric operations into one, renouncing the separate validity of each of them. This was the circumstance which made it hard for theoretical physicists to find their peace with the loss of CP-invariance.

The inequivalence of the direct and inverse flows of time (the "arrow of time"), the inequivalence of right and left, particles and antiparticles, all discovered in the past few years in the microcosm are long and well known in the macrocosm: we consist of nucleons and electrons, our heart is on the left, and we do all grow older. *What is the relation between the violation of* C, P, T in micro- and macrocosm? Does the CPT-invariance of the microcosm correspond to CPT-invariance of the macrocosm? These questions come to the mind of everyone who is dealing with the problem of discrete symmetries. Both these questions lead the one who asks them deeply into cosmology. Because it is well known that both the charge- and time-asymmetries of the Universe which surrounds us are consequences of particular "initial conditions" which have existed in the Universe approximately 10^{10} years ago.

The remaining chapters of this review are designed for readers–physicists who are familiar with the problem of CP-violation and would like to have a report on the latest events in this area. We shall discuss the fundamental facts and the fundamental theoretical models.

The experimental data in our possession can be divided into two groups: the first contains numbers characterizing the observed CP-noninvariant effects, and the second consists of upper bounds on unobserved effects. We shall enumerate the fundamental facts in the form in which they were known at the time of the Heidelberg conference (September, 1967) and then we point out the new data which have appeared in the most recent months.

I. OBSERVED CP-NONINVARIANT EFFECTS

Up to the present time the violation of CP-invariance has been observed in four processes; all of them involve decays of the long-lived neutral kaon K_L^0:

1.1. The decay mode $K_L^0 \to \pi^+\pi^-$ is characterized by the complex number η_{+-}, the ratio of the amplitude of this decay to the amplitude of the short-lived kaon $K_S^0 \to \pi^+\pi^-$:

$$\eta_{+-} = \frac{\langle \pi^+\pi^- | T | K_L^0 \rangle}{\langle \pi^+\pi^- | T | K_S^0 \rangle}.$$

The absolute value of this number is: $|\eta_{+-}| = (1.95 \pm 0.07) \times 10^{-3}$, its phase is $\Phi_{+-} = 65 \pm 20°$. One may expect a further increase in accuracy after the present experiments on precision measurement of δm (the $K_S^0 - K_L^0$ mass difference) will be finished.*

1.2. The mode $K_L^0 \to 2\pi^0$ is characterized by the number:

$$\eta_{00} = \frac{\langle \pi^0\pi^0 | T | K_L^0 \rangle}{\langle \pi^0\pi^0 | T | K_S^0 \rangle}.$$

The results of papers published in 1967 give a η_{00} of the order of 4×10^{-3} and have rejected the possibility that $\eta_{00} = \eta_{+-}$. However, during the last months there have appeared unpublished communications about new experiments indicating that η_{00} is substantially smaller than 4×10^{-3}, and is possibly close to 2×10^{-3}. The measurement of η_{00} is the object of a series of new experiments are being carried out currently. So far the phase Φ_{00} has not been measured.

1.3. The probability of the decay $K_L^0 \to \pi^- e^+ \nu$ turned out to be larger than the rate for the decay $K_L^0 \to \pi^+ e^- \bar{\nu}$: The magnitude of this charge asymmetry is measured by

$$\delta_e = \frac{N(e^+) - N(e^-)}{N(e^+) + N(e^-)} = (2.24 \pm 0.36) \cdot 10^{-3}.$$

---

*According to UCRL-8030, Aug. 1968: $|\eta_{+-}| = (1.89 \pm 0.04) \times 10^{-3}$, $\Phi_{\pm} = (49 \pm 8)°$

1.4. The rate of the decay $K_L^0 \rightarrow \pi^- \mu^+ \nu$ is larger than the rate of the decay $K_L^0 \rightarrow \pi^+ \mu^- \nu$:

$$\delta_\mu = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)} = (4.0 \pm 1.4) \cdot 10^{-3}.$$

For a detailed discussion of the experimental aspects of K_L^0-mesons cf. the report of C. Rubbia.

II. UNOBSERVED EFFECTS

The discovery of the decay $K_L^0 \rightarrow \pi^+\pi^-$ has activated the search for CP-, T- and CPT-violating effects in the decays of other particles and other reactions. None of these effects has been found, and the following limits have been established (in parentheses we indicate which of the invariances was subjected to test: C, T, CP, CPT; we indicate the most sensitive experiments by using boldface letters.

a) In kaon decays:

2.1. (CP). The rates of the modes $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^- \rightarrow \pi^-\pi^-\pi^+$ are equal to each other within 0.2%.

2.2. (CP). The spectra of the π^- in the decay $K^+ \rightarrow 2\pi^+\pi^-$ and of the π^+ in the mode $K^- \rightarrow \pi^-\pi^-\pi^+$ are equal, with an accuracy of approximately 20%.

2.3. (CP). The spectra of π^+ and π^- in the mode K $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ coincide with an accuracy of the order of 50% (more precisely, the spectra exhibit a difference, but it seems to be due to some systematic errors).

2.4. (CP) The decay mode $K_S^0 \rightarrow \pi^+\pi^-\pi^0$ was not observed. However the accuracy of these experiments is very low: one can only assert that the rate for this decay is not larger than the rate for the mode $K_L^0 \rightarrow \pi^+\pi^-\pi^0$. As we know, the decay $K_S^0 \rightarrow \pi^+\pi^-\pi^0$ can proceed both with and without CP-conservation.

2.5. (CP). No CP-violation related to a violation of the $\Delta Q = \Delta S$ rule has been observed in the decays K_{13}^0 and $\bar{K}_{13}^0$. For the parameter Im x which characterizes the CP and $\Delta Q = \Delta S$ violations one obtained Im x $\lesssim 0.25$.

2.6. (CP). The decays $K_L^0 \rightarrow \pi^0 e^+ e^-$ and $K_S^0 \rightarrow \mu^+\mu^-$ $(B < 7 \times 10^{-5})$* have not been observed.

2.7. (T). There is no muon polarization perpendicular to the decay plane of $K_{\mu 3}^0$, with an accuracy of 1.5%.

2.8. (CPT). The lifetimes of the K^+ and K^- mesons coincide within 0.1%.

b) In slow decays of other particles

3.1. (T). In the beta decay of the free neutron no T-odd correlation $\sin \varphi \xi_n (p_e \times p_\nu)$. The experiment of Erozolimskiĭ reported by him at this seminar implies that the relative phase φ of the axial vector and vector constants in neutron beta decay is smaller than 1.5° (the previous limit on φ was 6°).

3.2. (T). In β^+ decay of Ne^{19} the limit on the same phase is 2°.

3.3. (T). The shape of the spectrum and the electron polarization in the beta decay of RaE implies that the fundamental matrix elements cancel one another to a high degree of accuracy. This is only possible if $\varphi < 5°$.

3.4. (T). The relative phase of the s- and p-waves in the decay $\Lambda \rightarrow p\pi$ is $7 \pm 7°$ whereas $p\pi$-scattering yields 5–8°.

3.5. (CPT). The lifetimes of positive and negative pions coincide to an accuracy of 0.7%, those of the positive and negative muons coincide within 0.1%.

c) In strong and electromagnetic processes.

4.1. (CP). The CP-odd decay $\eta_0 \rightarrow \pi^0 e^+ e^-$ has not been observed (B < 0.1%).

4.2. (CP). No charge asymmetry A* has been observed in the decay $\eta^0 \rightarrow \pi^+\pi^-\pi^0$ (A < 1%).

4.3. (CP). No charge asymmetry A was observed in the decay $\eta^0 \rightarrow \pi^+\pi^-\gamma$ (A < 4%). The reports of Baglin and Finocchiaro at this seminar analyze these experiments in detail and discuss new, more accurate experiments which are now in the course of completion.

4.4. (CP). The positive and negative pion spectra in proton–antiproton annihilations coincide within a few percent. The same is true for the K^+ and K^- spectra.

4.5. (CP). There is no charge asymmetry A in the decay $X^0 \rightarrow \pi^+\pi^-\gamma$ (A < 15%).

4.6. (T). No electric dipole moment has been observed for the neutron. The latest results of Miller, reported here, give $d_n < e \times 3 \times 10^{-22}$ cm.

4.7. (T). The upper limit for the dipole moment of the cesium atom is $e \times (2.0 \pm 0.6) \times 10^{-21}$ cm. From this the authors deduce an upper limit on the electron dipole moment of $d_e = e \times (1.7 \pm 0.5) \times 10^{-23}$ cm. (This problem is discussed in detail in the talk of F. L. Shapiro.)

4.8. (T). The amplitudes of direct and inverse nuclear reactions are equal within a few tenths of a percent ($Mg^{24} + d \rightleftarrows Mg^{2}$%$+ p$, $Mg^{24} + \alpha \rightleftarrows Al^{27} + p$).

4.9. (CP). The decay $\pi^0 \rightarrow 3\gamma$ has not been observed $(B < 5 \times 10^{-6})$.

4.10. (CP). The decay of parapositronium into three photons has not been observed $(B \leq 2.8 \times 10^{-6})$.

4.11. (T). No T-odd correlation has been observed in the decay $\Sigma^0 \rightarrow \Lambda^0 e^+ e^-$ (with an accuracy of the order 10%).

4.12. (T). No T-violation has been observed in high energy pp scattering. The accuracy of these experiments is discussed in detail in the report by S. M. Bilen'kiĭ, L. I. Lapidus, and R. M. Ryndin.

4.13. (T). No T-odd $\beta\gamma\gamma$-correlations have been observed in nuclear decays $(\eta < 4 \times 10^{-2}$, where η is the relative phase of the matrix elements of the mixed transition).

4.14. (T). No T-odd $\gamma\gamma$ correlations have been observed after nuclear capture of a polarized neutron $(\eta < 2 \times 10^{-2})$.

4.15. (T). No T-odd $\gamma\gamma$ correlations have been observed by means of the Mössbauer effect $(\eta < 4 \times 10^{-3}$, cf. the report of N. A. Burgov).

4.16. (CPT). Particle and antiparticle masses are equal to each other within an accuracy of the order 10^{-2} for $\pi^\pm$, $K^\pm$ and of the order 10^{-4} for $\mu^\pm$.

4.17. (CPT). The magnetic moments of particles and antiparticles are equal within 2×10^{-5} (for $\mu^\pm$ and $e^\pm$). According to an unpublished result of Picasso (cf.

---

*Here and below B denotes the ratio of the width of the given decay mode to the total width of the particle.

* Here and below A denotes the charge asymmetry:

$$A = \frac{N^+ - N^-}{N^+ + N^-}.$$

Finocchiaro's report) the equality of magnetic moments for positive and negative muons has now been tested with an accuracy of 10^{-6}.

These are the facts in our possession. As a rule the accuracy of the corresponding experiments is still too small. However some of them (those which have been emphasized by boldface print) allow one to draw important physical conclusions.

III. MODELS FOR VIOLATION OF CP-INVARIANCE

Many hypothetical mechanisms for the violation of CP have been proposed. We are not able to discuss them all (cf. the reports of B. A. Arbuzov, M. Veltman and A. T. Filippov). In first approximation the known models can be divided into four groups, according to the magnitude of the constant f which measures the strength of the CP-violating interaction, and according to the selection rules involving hypercharge Y and parity P which are involved (cf. table).

In the absence of a whole series of experimental data, a comparative evaluation of the different models can only be subjective. Nevertheless, I shall attempt to evaluate the status of each of the models, utilizing a five-point grade system.

a) The electromagnetic interaction model is the most optimistic, and has predicted a series of effects, none of which has been found, despite the fact that the accuracy of these experiments (η^0-meson decays, neutron dipole moment[*]) exceeds the accuracy required of the experimentalists originally, on the basis of optimistic estimates. Of course, if one makes use of additional hypotheses (isospin selection rules, SU(3) etc.) each of these estimates can be lowered considerably. In particular many of the effects appear to be suppressed, if the CP-noninvariant photon vertices are isoscalar. For a verification of this possibility it would be useful to continue a high-accuracy search for charge asymmetry in the decay $X^0 \to \pi^+\pi^-\gamma$ and a measurement of the transverse polarization of recoil deuterons in ed-scattering.

Owing to the unreliable character of the estimates involving virtual hadrons, and to the fact that the initial form of the CP-noninvariant electromagnetic interaction is not fixed in the model, a final "closing" of the electromagnetic model may be a task of the relatively remote future. But today one is very tempted to give it a "failing grade."

Interaction table

Interaction	f	$\lvert \Delta Y \rvert^P$
Electromagnetic	$\sim e$	0^+
Millistrong	$\sim 10^{-3}$	0^+
Milliweak	$\sim 10^{-9} \approx 10^{-3}G$	1^-, 1^+, 2^-, 3^+
Nanoweak (superweak)	$\sim 10^{-15} \approx 10^{-9}G$	2^+

b) The model of a millistrong interaction. Strictly speaking, none of the (sufficiently prudent) predictions for the millistrong model has so far been proved false. There are however a few indirect doubts about this model. The absence of asymmetry in the decay $\eta^0 \to \pi^+\pi^-\pi^0$ indicates that the millistrong interaction does not seem to have a T = 2 component. On the other hand if $\eta_{00} \neq \eta_{+-}$ then this interaction must have components with $T \geq 1$ (the T = 0 component alone does not suffice). Apparently the component with T = 0 should manifest itself in experiments comparing the cross sections of direct and inverse reactions, whereas T = 3 should show up if one compares the widths of the decays $K^+_{3\pi}$ and $K^-_{3\pi}$, if one can raise the accuracy of these experiments by one order of magnitude. It seems to me that the millistrong model does not deserve more than a "passing grade."

c) The model of milliweak interaction. The predictions of this model are even more conservative and harder to verify. The experiments done so far are deficient in accuracy, at least by one order of magnitude, in order to test this model. (For a comparison of $K^+ \to 2\pi^+\pi^-$ and $K^- \to 2\pi^-\pi^+$ cf. the report of V. V. Anisovich; also the beta decay of the neutron.) We note that a negative result, e.g., in the beta decay, would not destroy the model, since it is not clear a priori whether the leptons do participate in the milliweak interaction, or only the hadrons.

Let us consider what advice other than "paternal" indications that higher accuracies are needed in already performed experiments, theorists could give to experimentalists in order to test the milliweak model.

It is obvious that it is best to search for manifestations of a CP-noninvariant interaction in processes where the CP-invariant amplitudes are for some reasons small. From this point of view the decay $K^+ \to \pi^+\pi^0$ is of interest, since its amplitude is about 20 times smaller than the amplitude of the decay $K^0_S \to \pi^+\pi^-$. If the CP-odd transitions of a kaon into a two-pion state with T = 0 and T = 2 are comparable in magnitude, then in the decay $K^+ \to \pi^+\pi^0$ the latter could yield a nonconservation of CP of approximately 4%. Unfortunately, it is impossible to detect the presence of a CP-noninvariant phase in the decay $K^+ \to \pi^+\pi^0$ (the probability is proportional to the absolute square of the amplitude). It could be detected however in the decay $K^+ \to \pi^+\pi^0\gamma$. Owing to interference of the bremsstrahlung amplitude and the amplitude for contact emission of a dipole photon, one might expect significant CP-noninvariant effects. In particular, a difference of the widths of the decays $K^+ \to \pi^+\pi^0\gamma$ and K^- could attain one percent. If this effect is discovered, it would be interesting for the clarification of its nature to investigate experimentally the CP-violation in the decays $K_{L,S} \to \pi^+\pi^-\gamma$. The presence of interference phenomena in these decays could indicate directly that CP is violated. Should it turn out that in the decay $K_L \to \pi \to \pi^+\pi^-\gamma$ CP is substantially less violated than in $K^+ \to \pi^+\pi^0\gamma$ this would mean that in the latter mode CP is violated in the bremsstrahlung amplitude, rather than in the contact amplitude. Should it happen that the effects

---

[*] The model of electromagentic CP-violation predicts the existence of a dipole moment of the neutron only in the case when there exists a weak interaction which does not change strangeness and violates the conservation of space parity. The existence of such an interaction predicted by the V-A theory has been recently confirmed by a series of experiments (cf. the tables of V. M. Lobashov and the report of I. S. Shapiro).

are comparable in both decays, this would mean that the CP-violation occurs in the contact amplitude and is closely related to the photon emission.

A revision of the experimental data referring to the weak interaction indicates that the theory of the universal V–A interaction is until now verified only with very low accuracy. Thus, it is not excluded that the relative phase of the axial vector and vector constants in muon decay is of the order of 15°. In beta decay there are experimental results contradicting the theory, e.g., the data on longitudinal polarization of the electron (cf. the report and the table of V. G. Erozolimskiĭ, and the review of I. I. Gurevich and B. A. Nikol'skiĭ).

There are also serious inconsistencies in the K-meson decays. Thus the data on spectra and relative rates for the decays K_{e3} and $K_{\mu 3}$ do not agree with the data on muon polarization in the $K_{\mu 3}$ decay within the framework of the universal V–A interaction (cf. the talk by Aubert).

Taking into account all this one may say that the hypothesis of milliweak interaction does, maybe, deserve a "B grade."

The electromagnetic and millistrong hypotheses which were discussed above suffer from a common defect: their predictions are not unconditional, and have a rough estimate character. Therefore these hypotheses are unable to provide a corresponding negative experimentum crucis. The same objection can also be raised against some of the versions of the milliweak model.

d) The superweak interaction model. A remarkable property of this model is the fact that it makes rigid predictions:

1. $|\eta_{+-}| = |\eta_{00}|$.
2. $\Phi_{+-} = \Phi_{00}$
3. $\Phi_{+-} = \arctan [2(m_L - m_S)/\Gamma_S - \Gamma_L] \simeq 43°$.
4. $\delta_e = \delta_\mu = 2|\eta_{+-}| \cos \Phi_{+-}$.
5. Other predictions, referring to the other decays, $K^0_{3\pi}$, $K^0_{2\pi\gamma}$ etc., which are rather difficult to verify, since the magnitude of the predicted effects is very small.
6. No observable CP-noninvariant effects except for those in K^0-meson decays.

The prediction 1 contradicts experiment, but it is not clear whether the corresponding experimental data are final.

Prediction 2 has not yet been tested experimentally.

Within the experimental errors, predictions 3 and 4 do not conflict with the experiments.

Prediction 6 agrees brilliantly with a wealth of negative results, which were obtained in searches for CP- and T-violations everywhere with the exception of K^0-mesons.

Thus, everything reduced to the experiment measuring the decay $K^0_L \to 2\pi^0$. If it turns out that $|\eta_{00}| \neq |\eta_{+-}|$, we shall grade the superweak interaction model "zero" and forget about it. Should it turn out that $|\eta_{00}| = |\eta_{+-}|$, the model will have to be given a higher grade, and the chances that it is wrong will be small, but nonvanishing.

Why would then experimental confirmations of a whole series of predictions of the superweak model not mean that the model is completely vindicated? There are at least two reasons for this.

First, an increase of precision of the experimental data might show some discrepancies with the model. Second, and more important, there are a series of models for which the predictions coincide in many points with those of the superweak interaction model.

For instance, milliweak models with the selection rules $|\Delta Y|^P = 1^+, 2^-, 3^+$ could lead to the observed $K_L \to 2\pi$ decays only in combination with the ordinary weak interaction via the transitions $K \leftrightarrow \bar{K}$ with $\Delta Y = 2$. The same is true for models in which the source of CP-violation are leptonic decays with a milliweak violation of the $\Delta Q = \Delta S$ rule. One can distinguish each of these models from the superweak interaction model only by means of investigating CP violation in the decays $K_{3\pi}$, K_{l3}, and by searching for decays with $\Delta Y \geq 2$ ($\Xi \to N\pi$, $\Omega^- \to N\pi$, etc.)

If the CP-violating superweak interaction is indeed realized in Nature, the chances of observing it in the decays of other particles are negligible. The probabilities of processes due to this interaction are by 18(!) orders of magnitude smaller than those of ordinary weak processes. One should not despair, however. It is not excluded that the superweak interaction could realize what the ordinary weak interaction cannot. As B. M. Pontecorvo has remarked in our seminar, the experiments searching for double beta decay have now attained a degree of accuracy such that, if the superweak interaction violates lepton number conservation ($\Delta L = 2$), such experiments could uncover this interaction. It is also conceivable that as the energy of colliding particles increases the superweak interaction becomes stronger. If it is related to some specific particles (e.g., to so-called a-particles) then beyond the production threshold of these particles their production cross section may turn out not to be "superweak" (such a model has been discussed several years ago).

Finally, the superweak interaction of ordinary particles with the so-called mirror particles may turn out to be observable. However the mirror particles already belong to the domain of fantasy, and I shall touch upon this question at the end of my review. And now let us turn to a more prosaic and much more urgent question.

IV. WHAT COULD FURTHER EXPERIMENTS WITH K^0 MESONS TEACH US?

An answer to this question is provided by the phenomenological analysis of K^0-meson decays. Thus what will we learn when reliable measurements of the parameters η_{+-}, η_{00}, δ_e, δ_μ, which characterize the CP-violation in neutral kaon decays, become available? Knowing these parameters will give us the possibility of determining the wave functions of the K^0_L and K^0_S and to verify CPT-invariance with unique accuracy; to verify the μ–e universality; to determine whether CP is violated in other channels than the 2π-channel; to determine the isospin amplitudes of the decays; to determine the charge-exchange amplitude $\pi^+\pi^- \to 2\pi^0$ and, finally, to judge on the validity of the various models. Let us consider in detail some of these assertions.

a) Test of CPT-invariance. It is known that the states $|K_L\rangle$ and $|K_S\rangle$ with definite lifetimes and masses are not orthogonal to one another. The measure of nonorthogonality, $\langle K_L | K_S \rangle$ is related to the decay amplitudes of the K_L^0 and K_S^0 through conservation of total probability (unitarity of the S-matrix), which leads to the simple relation

$$\langle K_S | K_L \rangle \left[i (m_L - m_S) + \frac{1}{2} (\Gamma_L + \Gamma_S) \right] = \sum_F \langle F | T | K_S \rangle^* \langle F | T | K_L \rangle.$$

Here the notations are almost self-explanatory: $\langle K_S | K_L \rangle$ is the inner product of the two states, F are the states into which the K_L and K_S mesons can decay.

We separate explicitly the channels $F = \pi^+\pi^-$, $2\pi^0$ and write the unitarity condition neglecting the terms Γ_L/Γ_S:

$$\langle K_S | K_L \rangle \left[i \frac{m_L - m_S}{\Gamma_S} + \frac{1}{2} \right] = B_S^{+-} \eta_{+-} + B_S^{00} \eta_{00} + \gamma. \qquad (*)$$

Here

$$B_S^{+-} = \Gamma_S (\pi^+\pi^-)/\Gamma_S, \quad B_S^{00} = \Gamma_S (\pi^0\pi^0)/\Gamma_S,$$
$$\gamma\Gamma_S = \sum_{F'} \langle F' | T | K_S \rangle^* \langle F' | T | K_L \rangle,$$

where F′ denotes all channels other than $\pi^+\pi^-$ and $2\pi^0$. The relation (*) can be represented in the complex plane by the polygon in Fig. 1.

If CPT-invariance is valid, the quantity $\langle K_L | K_S \rangle$ must be purely real, and can be determined from the magnitude of the charge asymmetry in the decays of K_L-mesons:

$$\delta_e = \langle K_S | K_L \rangle \frac{1 - |x|^2}{|1 - x|^2}.$$

Here, as before

$$\delta_e = \frac{N(e^+) - N(e^-)}{N(e^+) + N(e^-)},$$

and x denotes the ratio of the amplitudes with $\Delta Q = -\Delta S$ and $\Delta Q = \Delta S$; if $x = 0$, $\delta_e = \langle K_S | K_L \rangle$. If the degree of CP-violation in the F′ channels does not exceed that in the 2π channels ($\sim 10^{-3}$), the term γ can be neglected, since the widths of the F′ channels are by two–three orders of magnitude smaller than that of the 2π channel. However, direct experimental tests leave sufficiently wide margins for γ: $|\gamma| \lesssim 10^{-3}$. Should $|\gamma|$ turn out to be of the same order as $|\eta_{+-}|$ and $|\eta_{00}|$, then with an accuracy of approximately one percent the parameter γ should be purely imaginary (this is the way we represented it in Fig. 1). At present two sides of the polygon ($|\eta_{00}|$ and γ) are sufficiently badly known, and one angle Φ_{00} is completely unknown. When all these elements are measured the quadrangle will be doubly overdetermined. If one fails to make it close this signifies that CPT-invariance is violated.

It should be noted that the accuracy to which CPT-invariance is tested for the interactions responsible for the decays is in the case of K_L^0 mesons of the same order as the accuracy reached at present for the other particles ($K^\pm$, $\pi^\pm$, $\mu^\pm$). However the accuracy to which one tests CPT-invariance of interactions with Y = 0, in particular of the strong and electromagnetic interactions which give the main contribution to the particle masses in the K_L^0-experiments is by ten orders of magnitude better than in experiments involving other particles.

Should it happen that the phenomenological analysis of the K_L^0 decays indicates a CPT-violation, it will be interesting to check whether the analysis does not agree with an assumed T-invariance. Until now we have not one experimental fact indicating that T-invariance is violated. It is essentially a profound belief in the validity if the CPT theorem that forces us to the conclusion that the fact that the decay $K_L^0 \to \pi^+\pi^-$ is observed means the fall of both CP and T.

In the case of T-invariance the quantity $\langle K_S | K_L \rangle$ would be purely imaginary, and the quantity γ, if it is large, would be practically real. A diagram corresponding to the case when $\mathrm{Re} \langle K_S | K_L \rangle = 0$ is illustrated in Fig. 2.

We note that should it turn out that $\Phi_{+-} \simeq 40$–$60°$ and $|\eta_{00}| \simeq |\eta_{+-}|$ one would not be able to close the polygon in Fig. 2, owing to the smallness of γ, and one could consider T-violation as proved. A more detailed analysis of the question of testing CPT and T in K_L^0 decays can be found in the report by L. I. Lapidus.

The professional cold-bloodedness with which the possible modes of violation of CPT-invariance was discussed above, certainly does not imply that those who discuss this question do not grasp the fundamental importance of this invariance for contemporary elementary particle theory. On the contrary, just because of the fact that this invariance is related to the most profound concepts of the theory (the existence of particles and antiparticles, connection of spin and statistics; cf. the report of V. Ya. Faĭnberg), the experimental testing of this invariance is of fundamental interest.

b) The determination of isospin amplitudes is also one of the most important purposes of a phenomenological analysis of K_L^0 decays. The advantage of isospin amplitudes is the fact that their phases can be theoretically predicted.

If one accepts as the zero-order approximation the fact that the $\Delta T = 1/2$ rule is well satisfied in the K_S^0

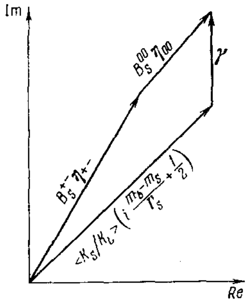

FIG. 1.

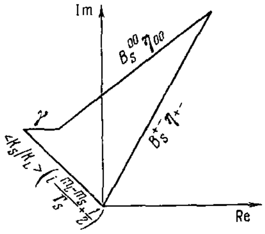

FIG. 2.

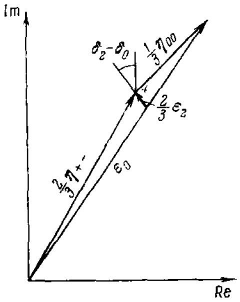

FIG. 3

$\rightarrow 2\pi$ decays (these experiments are not yet accurate), then using known Clebsch–Gordan coefficients it is not difficult to show that

$$\eta_{+-} = \varepsilon_0 + \varepsilon_2, \quad \eta_{00} = \varepsilon_0 - 2\varepsilon_2,$$

where

$$\varepsilon_0 = \frac{\langle\psi_0 | T | K_L\rangle}{\langle\psi_0 | T | K_S\rangle}, \quad \varepsilon_2 = \frac{1}{\sqrt{2}} \frac{\langle\psi_2 | T | K_L\rangle}{\langle\psi_0 | T | K_S\rangle},$$

and $|\psi_0|$ and $|\psi_2|$ denote 2π states with T = 0 and T = 2, T = 2, respectively.

Figure 3 illustrates the vectors ε_0 and $^2/_3\,\varepsilon_2$. The value of ε_2 also yields interesting information on the pion–pion phaseshifts: ε_2 must equal $\delta_2 - \delta_0 + (\pi/2)$ where δ_2 and δ_0 are the pion–pion phaseshifts in states with T = 2 and T = 0, respectively, at total c.m. energy equal to the kaon mass. The data on $\delta_2 - \delta_0$ which can be derived from other processes are discussed in detail by G. A. Leksin. It seems that they yield sufficiently reliable information on the absolute value ($|\delta_2 - \delta_0| \approx 50°$), but data on the sign of $\delta_2 - \delta_0$ obtained by means of different methods contradict each other.

We note that in the superweak interaction model $\varepsilon_2 = 0$, and the pion–pion phaseshift cannot be determined from K_L^0 decays.

In conclusion of this section it should be noted that a sufficiently exact measurement of the parameters of K^0 K_L^0 decays could "close" the superweak model and similar related milliweak models. However, as was stressed in particular by Wolfenstein in his report, this does not refer to the majority of other models, which give no clear-cut predictions for the parameters η_{+-}, η_{00} and δ and for which it would be necessary to measure effects outside the domain of K_L^0-mesons.

V. MIRROR SYMMETRY AND MIRROR PARTICLES

The already investigated CP-noninvariant effects alone make it possible for an isolated observer to determine uniquely what should be called a particle and what an antiparticle, what is left and what is right. Indeed, a beam of K_L^0 now defines uniquely what we ought to call a positron: the positron is that particle into which a K_L^0 decays more often in its K_{e3} mode. In terms of this it is easy to determine what is contained in the atoms surrounding the observer: electrons or positrons. And since the positrons resulting from K_{e3} decays are polarized in a right-hand manner, there appears an absolute definition of right-handedness and left-handedness.

The concepts of right-handedness and left-handedness would be restored to their relative character, if it should turn out that in addition to ordinary particles there also exist mirror particles, such that for any natural process there is also possible its "mirror-image" process. It follows from the available experimental data that the interaction of mirror-particles with "our" particles can be neither strong, electromagnetic nor even weak. However the existing experimental data do not exclude the existence of a milliweak and superweak interaction which could lead to interesting observable effects. These effects would manifest themselves best in the case of neutral K mesons. According to the hypothesis under discussion, there exist four neutral K mesons: two long-lived and two short-lived ones, such that the masses and lifetimes of all four are different. The total Lagrangian must be invariant under a CPA-transformation, where A replaces particles by their mirror-images and vice versa. Thus one of the long-lived K mesons must be even under CPA (K_L^e) and the other—odd (K_L^o the same being true for the short-lived ones (K_S^e and K_S^o). In the strong interactions occurring in "our" accelerators only "our" K mesons are produced. However in vacuo, owing to oscillations analogous to the ones well known for ordinary K^0 mesons there will occur a slow transition of "our" K mesons into mirror K mesons. Intercepting a beam of such mesons by a thick wall which would absorb all our particles one could end up behind the wall with a pure beam of mirror particles. Owing to the same oscillations, the latter should slowly transform into "our" K mesons which decay into "our" pions, muons, electrons, etc., and can thus be detected. These were the conditions realized in the neutrino experiment, where the detectors were shielded from the primary beam by a steel wall of 25 m thickness. Analyzing this experiment one can conclude that the transition time of "our" mesons into mirror K^0 mesons is at least by two orders of magnitude larger than the lifetime of the K_L^0 meson. It would be interesting to consider special experiments in which the detector behind the shield would be situated away at a distance of the order of the decay length of the K_L meson, since the number of three-particle K_L decays should increase proportionally to the square of the distance up to distances $l = 2\gamma\tau_L c$.

Insofar as a direct clarification of the one- or two-exponential decay character of the K_L meson is concerned, these experiments are less sensitive in the framework of the model of mirror particles than the "experiments behind the wall" described above. However, experiments verifying the exponentiality of decays may present interest even outside the model of mirror particles. The assertion that the observation of the effects 1.1–1.4 in K_L^0 decays proves a violation of CP-invariance is based on the assumption that in a K_L^0-beam there do not exist two coherent components, but only one, decaying both into two and three pions. It is without doubt that this assumption is more than likely to be true, since up to now no satisfactory CP-invariant model with two coherent long-lived K-beams has been proposed. (We recall that the so-called "shadow Universe" model was in contradiction with the data of the neutrino experiment.

However, the experimental data strengthening the assertion that the K_L^0 meson is indeed one, are still sufficiently scant. Thus the exponentiality of K_L^0-decays is still verified with low accuracy, and the constancy of the relative widths of the decay mode $K_L \rightarrow 2\pi$ has been tested only in the interval $0.15 < t/\tau_L < 0.80$ with an accuracy of the order of 10%. (Cf. the table of N. N. Nikolaev.) It would be desirable to increase the accuracy of these measurements and to extend them to larger values of t.