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POSSIBLE NONCONSERVATION OF COMBINED PARITY IN WEAK INTERACTIONS

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In August, 1964 at the International Conference on High Energy Physics at Dubna sensational results were reported obtained by a group of experimental physicists from Princeton University in the U.S.A. Christenson, Cronin, Fitch and Turlay observed the decay into two π mesons of the long-lived component in the K_0 meson beam obtained from the Bookhaven proton accelerator.

The results of this experiment have already been published (cf. [1]), and if they are confirmed their consequences for physics will be very serious. The data of this experiment appear to provide evidence for the violation manifested in weak interactions of CP-invariance of nature*. Such a conclusion is, strictly speaking, not unambiguous. Other possibilities also exist. But they are all associated with radical changes in our concepts. We shall discuss below the physical consequences of the experiment.

The K_0 meson created in nuclear collisions during times of the order of 10^{-23} sec is a state of definite strangeness $S = 1$. Its antiparticle $\overline{K}_0$ has the strangeness $S = -1$, and since the weak interaction can alter strangeness, the transitions $K_0 \rightleftarrows \overline{K}_0$ are possible. In spite of the fact that in such transitions the strangeness is altered by two units, and that they are second order processes with respect to the weak interactions, nevertheless a profound rearrangement of the K_0 and $\overline{K}_0$ states occurs, because the corresponding levels are degenerate. (For a more detailed discussion of the concept "strangeness" and for the definition of the K-meson states cf., for example, the review article by Zel'dovich [3].) If the CP-invariance were to hold rigorously, then the states between which there are no transitions and which have a definite mass and a definite lifetime would be the CP-even and the CP-odd combinations of K_0 and $\overline{K}_0$. They are respectively called K_1 and K_2. The K_1 meson basically decays into two π mesons. For K_2 such a decay is forbidden by the conservation of CP-parity (a system of two π mesons has positive CP-parity). The K_2 meson can decay into three π mesons, and also into a π meson, an electron (or a μ meson) and a neutrino, because these states do not have a definite CP-parity. (For greater details on the decay of K mesons see the review article by L. B. Okun' [4].) Because of the different modes of decay the lifetimes of K_1 and K_2 are quite different. The K_2 meson "lives" 600 times longer than the K_1 meson ($\tau_{K_1} \approx 10^{-10}$ sec, $\tau_{K_2} \approx 6 \times 10^{-8}$ sec). In the experiment of Christenson, Cronin, Fitch and Turlay the K mesons had a velocity $v \approx 0.91c$. Therefore, the K_1-meson should decay along a path of length $v\tau_{K_1}(1 - v^2/c^2)^{-1/2} \approx 6.5$ cm; however, disintegrations into two π mesons were observed at distances ≈ 19 m from the point at which K_0 mesons were created. It is true that the number of such decays is not large and amounts to 0.2% compared to the ordinary events $K_2 \to 3\pi$, $K_2 \to \pi e \nu$ and $K_2 \to \pi\mu\nu$. Nevertheless, it is very difficult to explain the figure of 0.2%.

Indeed, as we have explained, only the K_1 meson can decay into two π mesons. But in accordance with the modern concepts concerning the decay law of an unstable particle the admixture of K_1 mesons at a distance which is approximately equal to 300 decay lengths must be by many orders of magnitude smaller than the value required to explain the observed effect. Since the experiment was not carried out in vacuum, K_1 might be formed from K_2 as a result of the interaction of the latter with matter. Such a phenomenon is called regeneration. However, the fraction of K_1 mesons formed from K_2 in the regeneration process in matter present in the experimental arrangement is according to the author's estimates smaller by factor of 10^6 than what is required.

Thus, if the data of the Princeton group are confirmed, we shall be forced to conclude that apparently one of several possibilities which are new from the point of view of modern physics is realized.

1) Deviations from the exponential decay law possibly arise for times which are much greater than the lifetime of an unstable particle; therefore a sufficiently large admixture of K_1 mesons "survives" and decays at large distances from the point of creation. There exist theoretical considerations (cf., for example, [5,6]) favoring the view that the exponential law of decay may be only of an approximate nature. However, until now it has been assumed that this effect is too small to make it necessary to take it into account in practice.

*The invariance of nature with respect to transformations of combined inversion together with the conservation of CP-parity associated with it, is a beautiful hypothesis which was first proposed by Landau[2]. After it was determined experimentally in 1956 that the spatial (P) parity was not conserved in weak interactions, the hypothesis of the conservation of CP-parity was required in order to preserve the invariance of empty space (vacuum) with respect to mirror reflection (spatial inversion).

2) Some new kind of a field may exist. K_0 and $\overline{K}_0$ can interact with it in different ways. On being scattered by such a field K_2 will go over into K_1, and after this K_1 will decay into two π mesons. In connection with such a possibility several specific models have already been proposed (cf., for example, the papers by Bernstein, Cabibbo and Lee [7] and by Bell and Perring [8]). The new field can interact with strangeness or with the hypercharge (K_0 and $\overline{K}_0$ have different values of the hypercharge and of strangeness). It is sufficient for the K mesons to have a potential energy $\sim 10^{-8}$ eV in such a field in order for the observed effect to arise. This is associated with the fact that the difference in the masses of K_1 and K_2 is very small ($\sim 10^{-5}$ eV) and this system is sensitive to weak potentials. Unfortunately, it is very difficult to suggest other situations where such an interaction which turns out to be weaker than gravitation by 10 orders of magnitude could manifest itself.

3) A new particle may exist, which interacts with strangeness (cf., the paper by Levy and Nauenberg [9]). The transformation of K_2 into K_1 takes place accompanied by the emission of such a particle. If one assumes that its mass is only a little smaller than the difference between the masses of K_2 and K_1 then its interaction with the "strangeness charge" of K mesons must be determined by the dimensionless constant $g^2/4\pi \approx 10^{-5}$. This is only by three orders of magnitude smaller than the square of the electromagnetic constant.

Finally, perhaps there exists still another possibility which cannot be envisioned now. Many people believe that in future some simple explanation will be found of why in the experiment of Christenson, Cronin, Fitch and Turlay decays into 2π are observed. The basis for such a belief is the physicists' natural unwillingness to introduce radical changes in established concepts on the basis of the data of a single experiment which is, moreover, carried out on a very complex object.

4) After all this has been said we must discuss the most direct method of interpreting the data on the decay of K_2 as evidence for the violation of CP-invariance. At the same time the T-invariance of weak interactions must be placed in doubt.* It is essential to note that until now there are no experiments which reliably establish the conservation of CP- and T-parity in decays in which strangeness changes. Moreover, there are no experiments at all in which CP- and T-invariance could be checked in leptonic decays with a change of strangeness.

After the epic events of 1956-1957 associated with the non-conservation of parity, it is difficult to surprise a physicist with anything. If it should turn out that experiment demands this, it will be necessary to renounce CP as well, no matter how difficult this step appears to be now.

An unusual aspect of the situation emerging at present is also the fact that the nonconservation of CP-parity appears to be a very weak effect. According to the results of the Princeton group the amplitude of the process $K_2 \rightarrow 2\pi$ is smaller by approximately a factor of 2×10^{-3} than the amplitude of $K_1 \rightarrow 2\pi$.

One might postulate, and, possibly, this will indeed turn out to be the case, that the weak interaction (or in any case that part of it which gives rise to the nonleptonic decays of the K_0 mesons) actually violates the CP-invariance weakly (the corresponding amplitudes are suppressed by a factor of 1000). Such an assumption does not contradict other experiments. This possibility, apparently, can not be excluded even from the ordinary β-decay. The accuracy attained there is insufficient to discover such an insignificant effect of the nonconservation of CP-parity.

However, all this bears very little resemblance to the manner in which P-parity is not conserved in weak interactions. Therefore, physicists are beginning to reason in the following manner: if we observe a small effect of nonconservation of P-parity in processes which occur mainly as a result of strong or electromagnetic interactions, then we know that this is due to weak interactions, where such nonconservation is the maximum one possible; we have now discovered a weak violation of CP-invariance in nonleptonic decays of the K_0 meson, so let us ascribe this to the influence of interactions of a different class. The decays corresponding to such interactions are suppressed with respect to the nonleptonic decays of K_0, but the nonconservation of CP in such transitions is considerable.

A model has been proposed (cf. Truong [10]) in which the violation of CP-invariance is due to interactions which change the isotopic spin by a large amount ($\Delta T = 3/2$). It is known experimentally that transitions with $\Delta T = 3/2$ are approximately by three orders of magnitude less probable than transitions with $\Delta T = 1/2$. Therefore, in such transitions one can assume a relatively greater violation of CP. In order to explain the effect it is necessary to introduce nonconservation of CP-parity in $\Delta T = 3/2$ transitions at a level of several percent. In this model K_2 decays directly into two π mesons in the $T = 2$ state (we recall that the isotopic spin of K is equal to $1/2$), while decay into the state $T = 0$ occurs in accordance with

$$K_2 \xrightarrow[CP \neq 1]{\Delta T = 3/2} 2\pi \qquad \xrightarrow[CP = 1]{\Delta T = 3/2} K_1 \xrightarrow[CP = 1]{\Delta T = 1/2} 2\pi.$$

*The invariance of any physical theory with respect to the product of the three operations: charge conjugation (C), spatial inversion (P) and time reversal (T) follows from some very general physical principles. The remarkable fact was first established by Lüders and Pauli and is called the "CPT-theorem." From the CPT-theorem it follows that if CP-invariance is violated then T-invariance is also violated.

Recently Sachs has investigated another possibility [11]. If we admit leptonic decays in which the changes in the strangeness and in the charge of strongly interacting particles are of opposite sign ($\Delta S = -\Delta Q$), then a combination of such processes with the ordinary decays $\Delta S = \Delta Q$ will lead to a mixing of the states K_0 and $\overline{K}_0$, for example, in accordance with the sequence $K_0 \rightarrow \pi e \nu \rightarrow \overline{K}_0$. If we now assume that in such processes CP-parity is strongly nonconserved, then in their turn K_1 and K_2 will be transformed into one another. However, this will occur slowly, because K_1 and K_2 have different masses and the difference in their masses is considerably greater than the interaction which leads to the leptonic transitions. Numerical estimates made by Sachs enable one to explain the observed effect quantitatively. Thus, in this model it is not the K_2 meson which decays into 2π violating CP, but K_2 slowly transforms into K_1 which in turn rapidly decays into 2π violating CP, but K_2 slowly transforms into K_1 which in turn rapidly decays into 2π conserving CP-parity. A serious argument against such a model is the circumstance that disintegrations with $\Delta S = -\Delta Q$ have not been observed experimentally. This can be explained only with difficulty, and then only by introducing a number of additional assumptions.

There exists an attempt to introduce a new very weak interaction which gives rise to transitions with $\Delta S = 2$ and with a maximal violation of CP (cf., Wolfenstein [12]). In this case the transitions $K_2 \rightarrow K_1$ with a subsequent rapid decay of the K_1 meson are already possible in the first order in this interaction. The new interaction must be weaker by a factor of 10^7–10^8 compared to the ordinary weak interaction.

Recently Cabibbo [13] has investigated the possibility of a violation of CP-invariance by associating it with the so-called currents of the second kind, which until now were thought to be absent. However, in this case the smallness of the ratio of the amplitudes of $K_2 \rightarrow 2\pi/K_1 \rightarrow 2\pi$ appears more as an accidental fact, and this should be regarded as a deficiency of the model.

The rapid appearance of a large number of quite different hypotheses characterizes the indefiniteness of the present situation and the insufficiency of our knowledge in this field. In the very near future we can expect many other proposals, but true understanding will arise possibly only as a result of future experiments.

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