to E. L. Feinberg and M. L. Ter-Mikaelian for constant interest in this work and for valuable discussions.

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251

## Two Possible Schemes of Non-Conservation Of Parity in Weak Interactions

B. L. IOFFE

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ONE OF THE possible explanations of the decay of $K^+$-mesons into two and three $\pi$-mesons consists in the supposition that spatial parity is not conserved in weak interactions[1]. If one accepts this hypothesis then the question arises: should charge parity and parity relative to reflection in time be conserved in weak interactions. As is well known[2], the connection between spin and statistics requires that all interactions be invariant under the product of the three transformations: reflection of the three spatial coordinates $I$, reflection in time $T$ and charge conjugation $C$, *i.e.*, symbolically $ITC = 1$. Therefore[3] with violation of spatial parity in weak interactions ($I \neq 1$) there are three possibilities: I) weak interactions are invariant under reflection in time ($T = 1$), but are not invariant under charge conjugation, so that $IC = 1$; II) weak interactions are invariant under charge conjugation ($C = 1$) but are not invariant under reflection in time and $IT = 1$; III) weak interactions are not invariant under either charge conjugation or reflection in time, but $ITC = 1$. If one accepts the last possibility, then the fact that a $K^0$-meson with a long lifetime exists[4] would appear to be a pure coincidence in so far as the argument of Gell-Mann and Pais[5], on the basis of which it was predicted, and would be valid only under conservation of either charge parity or parity relative to reflection in time. This forces us to discard the third possibility and consider only the first two.

In this article we consider what physical phenomena could occur with either of these alternative possibilities.

The first of these possibilities, as remarked by Landau[6], corresponds physically to the assumption that all interactions are invariant under simultaneous interchange of right and left and change from particle to antiparticle. The physical significance of the second assumption is that all interactions remain unchanged only if the motion proceeds backwards in time together with the transition from right to left.

We consider first scheme I, *i.e.*, when, together with violation of spatial parity, invariance relative to reflection in time is conserved. At $t \to -\infty$ let there be a system of particles in state $a$, with particle momenta $\mathbf{p}_a$ and a mean value of spins $\mathbf{s}_a$. Let, further, as a result of interaction, this system go into a different system of particles (at $t \to \infty$) with momenta $\mathbf{p}_b$ and mean values of the spins $\mathbf{s}_b$. From the invariance under reflection in time it follows[7] that the transition matrix element $S^I_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b)$ is connected in the following way with the matrix element of the inverse process $S^I_{ba}(\mathbf{p}_b, \mathbf{s}_b; \mathbf{p}_a, \mathbf{s}_a)$

$$S^I_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b) = S^I_{ba}(-\mathbf{p}_b - \mathbf{s}_b; -\mathbf{p}_a, -\mathbf{s}_a). \quad (1)$$

The matrix element $S_{ba}$, viewed as a function of its arguments $\mathbf{p}_a$, $\mathbf{p}_b$, *etc.*, does not have, in general, the same functional form as the function $S_{ab}$. Thus, we cannot extract any help directly from Eq. (1). However, if the transition $a \to b$ is considered to go as a result of a weak interaction, then in the first non-vanishing approximation of this interaction, the relation of detailed reversibility holds:

$$S_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b) = -S^*_{ba}(\mathbf{p}_b, \mathbf{s}_b; \mathbf{p}_a, \mathbf{s}_a). \quad (2)$$

[For the validity of (2) it is important that the transition proceed as a result of a weak interaction, but it is not necessary that the particle motion as a whole in the initial or final states be describable by free wave functions.] Eliminating $S_{ba}$ from Eqs. (1) and (2), we find that in the case of invariance of the interaction under reflection in time, the transition matrix element should satisfy the equation

$$S^{I}_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b) = -S^{I*}_{ab}(-\mathbf{p}_a, -\mathbf{s}_a; -\mathbf{p}_b, -\mathbf{s}_b) \quad (3)$$

and, consequently, the transition probability

$$W^{I}_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b) = W^{I}_{ab}(-\mathbf{p}_a, -\mathbf{s}_a; -\mathbf{p}_b, -\mathbf{s}_b). \quad (A)$$

In the case of the second possible scheme, where all interactions are invariant under charge conjugation, one can carry out analogous arguments. Only here, instead of reflection in time, it is necessary to consider the transformation of reflection of all four coordinates. The matrix elements of the direct and inverse transitions turn out to be connected by the following relation:

$$S^{II}_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b) = S^{II}_{ba}(\mathbf{p}_b, -\mathbf{s}_b; \mathbf{p}_a, -\mathbf{s}_a). \quad (4)$$

For the validity of Eq. (2), it is only necessary that the interaction Hamiltonian be hermitean, which, obviously, occurs also in this case. Substitution from Eq. (2) into Eq. (4) gives

$$S^{II}_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b) = -S^{II*}_{ab}(\mathbf{p}_a, -\mathbf{s}_a; \mathbf{p}_b, -\mathbf{s}_b). \quad (5)$$

Thus, in the case of scheme II, the transition probability should satisfy the equation

$$W^{II}_{ab}(\mathbf{p}_a, \mathbf{s}_a; \mathbf{p}_b, \mathbf{s}_b) = W^{II}_{ab}(\mathbf{p}_a, -\mathbf{s}_a; \mathbf{p}_b, -\mathbf{s}_b). \quad (B)$$

Using (A) and (B) it is easy to establish the general form of the transition amplitudes for both possible schemes of non-conservation of parity.

We consider, for example, the decay of a stationary polarized $\lambda$-particle, $\lambda^0 \to p + \pi^-$. In this case, the $\lambda$-particle decay is characterized by three vectors: the spin vector of the $\lambda$-particle $\mathbf{s}_\lambda$, the proton momentum $\mathbf{p}_p$ and the proton spin $\mathbf{s}_p$. We will be interested only in pseudoscalar quantities, arising because of non-conservation of parity. From these three vectors it is possible to construct three such quantities: $\mathbf{s}_p\mathbf{p}_p$, $\mathbf{s}_\lambda\mathbf{p}_p$ and $[\mathbf{s}_\lambda\mathbf{s}_p]\mathbf{p}_p$. From Eqs. (A) and (B) it then follows that in the case of scheme I the probability can contain terms proportional to $\mathbf{s}_p\mathbf{p}_p$ and $\mathbf{s}_\lambda\mathbf{p}_p$ whereas in the case of scheme II only terms proportional to $[\mathbf{s}_\lambda\mathbf{s}_p]\mathbf{p}_p$ can enter into the probability. Thus in scheme I, upon decay of the $\lambda^0$-particle one can expect polarization of the decay protons parallel (or anti-parallel) to the direction of their momenta, and, if the $\lambda$-particle is polarized, most of the decay protons will have momenta parallel (or anti-parallel) to the spin of the $\lambda$-particle. (This effect was considered by Lee and Yang[1].) In scheme II the effect of non-conservation of parity can be detected only by observing the polarization of the protons in decay of polarized $\lambda$-particles, or, equivalently, by measuring the directions of the momentum and spin of the proton relative to the normal of the plane in which the $\lambda$-particle was produced.

| Type of decay | Scheme I $T$ = inv. | Scheme II $C$ = inv. |
|---|---|---|
| $\Lambda$ | $\mathbf{s}_p\mathbf{p}_p$; $\mathbf{s}_\Lambda\mathbf{p}_p$ | $[\mathbf{s}_\Lambda\mathbf{s}_p]\,\mathbf{p}_p$ |
| $\beta$ | $\mathbf{s}_e\mathbf{p}_e$; $\mathbf{s}_e\mathbf{p}_N$ | $[\mathbf{s}_e\mathbf{I}_N]\,\mathbf{p}_e$ |
| | $\mathbf{I}_N\mathbf{p}_e$; $\mathbf{I}_N\mathbf{p}_N$ | $[\mathbf{s}e\mathbf{I}_N]\,\mathbf{p}_N$ |
| $\pi$ | $\mathbf{s}_\mu\mathbf{p}_\mu$ | — |
| $\mu$ | $\mathbf{s}_\mu\mathbf{p}_e$; $\mathbf{s}_e\mathbf{p}_e$ | $[\mathbf{s}_\mu\mathbf{s}_e]\,\mathbf{p}_e$ |

Analogously, one can determine the pseudoscalar quantities acceptable in each scheme for other weak decays. The results given in the table (the indices $\lambda$, $p$, $e$, $\mu$ denote the spin and momenta of the respective $\lambda^0$, proton, electron, $\mu$-meson; in the case of $\beta$-decay: $I_N$ is the spin of the initial nucleus, $\mathbf{p}_N$ is the nuclear recoil momentum, the remaining momenta are averaged over).

It is interesting to note that dipole moments of the nucleus are absent[6] in scheme I, but can occur in scheme II. In fact, the energy of interaction of a dipole moment with an electric field is proportional to $\mathbf{sE}$. Under time reflection, $\mathbf{s} \to -\mathbf{s}$ and $\mathbf{E} \to -\mathbf{E}$, and under reflection of all four coordinates $\mathbf{s} \to -\mathbf{s}$ and $\mathbf{E} \to -\mathbf{E}$ so that $\mathbf{sE} \to -\mathbf{sE}$ in scheme I and $\mathbf{sE} \to \mathbf{sE}$ in scheme II.

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252

## Non-Conservation of Parity and Hyperon Decay

S. G. MATINIAN
*Institute of Physics, Academy of Sciences, Georgian SSR*

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THE NON-CONSERVATION of parity in weak decay interactions[1,2] leads to a series of effects, the study of which allows one to establish whether, in reality, weak interactions are non-invariant relative to reflection of spatial coordinates, and also to clarify a number of other questions connected with this. In this note, the decay of hyperons by interactions which do not conserve spatial parity is considered. For simplicity we restrict ourselves to non-derivative couplings and to hyperon spins equal to ½.

The interaction Hamiltonian leading to the decay has the form

$$H = g\overline{\psi}_N (1 + \lambda\gamma_5)\, \psi_Y \varphi_\pi^* \qquad (1)$$

where $\psi$ are spinor wave functions and $\varphi_\pi$ is the wave function of the $\pi$-meson; $\lambda$ is a quantity, which is complex in general, characterizing the degree of non-conservation of parity. The existence of $K^0$-particles with long lifetimes[3] can be made compatible with non-conservation of parity if we assume that either temporal or charge parity is conserved (see Ref. 4 with regard to this). In the first case $\lambda$ is a real constant, in the second purely imaginary.

We now consider a hyperon at rest, the spin of which is directed along the unit vector $\boldsymbol{\eta}$. Calculation of the square of the matrix element $M$ of the interaction (1), leading to emission of a nucleon with a given direction of momentum $\mathbf{n}$ and spin along the unit vector $\boldsymbol{\zeta}$, gives

$$|M|^2 = \frac{1}{4}\Big\{\Big(1+\frac{m}{E_N}\Big)(1+\eta\zeta) + |\lambda|^2\Big(1-\frac{m}{E_N}\Big)(1-\eta\zeta)$$
$$+2\,|\lambda|^2 p^2\,[(\mathrm{n}\eta)\,(\mathrm{n}\zeta)/E_N(E_N+m)] \qquad (2)$$
$$+(\lambda+\lambda^+)\frac{p}{E_N}(\mathrm{n}\eta+\mathrm{n}\zeta) + i\,(\lambda-\lambda^+)\frac{p}{E_N}(\mathrm{n}\,[\eta\zeta])\Big\}.$$

Here $m$ is the mass of the nucleon, $E_N = \sqrt{p^2+m^2}$, $p = \sqrt{2\mu^* Q}$, where $\mu^*$ is the reduced mass of the $\pi$-meson and nucleon; $Q$ is the energy of decay of the hyperon; $\hbar = c = 1$. The first three terms in the braces correspond to the usual treatment with conservation of charge for even (terms with $|\lambda|^2$) and odd (terms without $|\lambda|^2$ hyperons. Non-conservation of parity leads to the appearance of the pseudoscalar (relative to spatial reflection) quantities: $\mathbf{n}\boldsymbol{\eta}$, $\mathbf{n}\boldsymbol{\zeta}$, $\mathbf{n}[\boldsymbol{\eta}\times\boldsymbol{\zeta}]$.

If the Hamiltonian $H$ is invariant relative to time-reflection, then the term $\mathbf{n}[\boldsymbol{\eta}\times\boldsymbol{\zeta}]$ drops out. In this case, contrary to the usual situations, even in the decay of unpolarized hyperons (absence of the term with $\boldsymbol{\eta}$) there will be a term of the order of the nucleon velocity ($v/c$) giving nucleons polarized along $\mathbf{n}$. This term would be particularly noticeable for $\Sigma$-hyperons.

In case of invariance of $H$ relative to charge conjugation the terms with $\mathbf{n}\boldsymbol{\eta}$ and $\mathbf{n}\boldsymbol{\zeta}$ drop out and the term proportional to $\mathbf{n}[\boldsymbol{\eta}\times\boldsymbol{\zeta}]$ remains, giving an additional correlation of the spins of the polarized hyperons and nucleons, different from that which would occur for variants with conservation of parity (this term leads to a mutually-perpendicular orientation of the spins). A similar situation arises in the case of gradient coupling.

Ioffe[5] arrived at analogous conclusions, starting from general considerations (within the framework of perturbation theory), about invariance of the decay probabilities relative to time-reflection and charge conservation, respectively.

In conclusion, we note that if there is invariance under reflection in time, then non-conservation of parity leads to correlation between the direction of emission of the $\Lambda^0$-particle in the decay of the $\Xi^-$-hyperon and the direction of emission of the nuclei in the rest system of the $\Lambda^0$-particle in its subsequent decay, even for a $\Lambda^0$-spin equal to ½. A simple consideration leads to a correlation function of the form $a + b\cos\vartheta$, where $\vartheta$ is the angle between the directions indicated above.