# PARITY NONCONSERVATION IN STRONG INTERACTIONS OF STRANGE PARTICLES

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A modification of Lee and Yang's theory of strange-particle parity doublets is considered in which parity conjugation invariance is extended to weak interactions. As a result parity nonconservation in weak interactions is found to be closely related to a change in strangeness.

Results of the analysis pertaining to the "forward-backward" asymmetry of the hyperon decay products are compared with the corresponding consequences due to parity nonconservation in strange particle production and interaction processes. Both interpretations are found to yield the same results as far as particles with odd strangeness are concerned. The two approaches can be distinguished by studying processes involving $\Xi$ hyperons.

## 1. INTRODUCTION

THE question of parity nonconservation in strong interactions of elementary particles has recently come to hold considerable interest.[1-7]

Starting from a renormalizable Yukawa interaction for elementary particles, Solov'ev[1-4] has shown that the requirement of CP invariance for the Lagrangian together with the laws of charge conservation and isotopic invariance results in space parity conservation for electromagnetic and strong interactions of ordinary particles. On the other hand CP invariance and isotopic invariance do not lead to space parity conservation for strong interactions involving strange particles — isotopic-invariant additions to the usual Lagrangian, which violate parity conservation, are possible.

Parity nonconservation in strong interactions involving strange particles should lead to the appearance of a component of the polarization vector in the plane of their production and should result in a "forward-backward" ("right-left") asymmetry in the distribution of the decay products. So far experiments have given no evidence for the existence of such an asymmetry,[6] although one cannot exclude the possibility that the angular dependence of the longitudinal polarization is such that a vanishing asymmetry results after averaging over the angle of emission of the hyperons. It is also possible that this polarization will become detectable as the energy of strange particle production increases.

In this paper we wish to show that effects arising from parity nonconservation in strong interactions of strange particles, in particular the above-mentioned asymmetry, would also arise in a parity-conserving theory, namely, a modification of the parity-doublets theory of Lee and Yang[8,9] which would not contradict any other experimental facts.

## 2. STATEMENT OF THE PROBLEM

We amplify the Lee and Yang parity-doublets hypothesis by the requirement that all weak (and electromagnetic) as well as strong interactions of elementary particles be invariant under the CP operation of parity conjugation $\theta \longleftrightarrow \tau$, $\Lambda_1 \longleftrightarrow \Lambda_2$, etc. In this way parity doubling of all particles with odd strangeness is introduced.

It is easy to see that this requirement automatically leads to parity nonconservation in weak interactions of strange particles whenever strangeness changes by an odd number.* Indeed in such cases we have strange particles with odd strangeness before ($\Lambda$-, $\Sigma$- and K-decays) or after ($\Xi$-decay) the decay. The requirement that the decay process be invariant under parity conjugation then results in either the decay of particles of opposite parities into ordinary particles in the same orbital states or (in the $\Xi$-decay case) the decay of a strange particle of definite parity into a strange particle of one or the other intrinsic parity, the decay products being in the same orbital states in both cases. As a result, parity nonconservation in the decay is closely related to the change in strangeness.

Extending CP invariance to the decays causes the parity doublets to have the same lifetime and

*It is interesting to note that the decay $\Xi \to n + \pi$ for which $\Delta S = 2$, would be parity conserving were it to exist.

not to differ from each other in either weak or strong interactions. Consequently the question of the existence of a long-lived component of the $\Sigma$-hyperon parity doublet, not found in the experiments of Alvarez,[10] does not arise.

It is obvious that all known experimental facts which can be explained by the theory with parity nonconservation in decays without doubling the number of particles can also be explained by the present approach.

The existence of K-particle doublets permits the introduction in a natural way of a strong $KK\pi$ interaction, which leads to a number of experimentally-confirmed consequences. However this interaction may also be introduced in Solov'ev's theory, where there is no need for parity doublets, since the conservation of combined parity permits the Lagrangian of a strong (parity violating) local $KK\pi$ interaction to be written in the form

$$L_{K\pi} = ig_{K\pi} \{K^+ K_0 \Phi + K K_0^+ \Phi^+\},$$

where $\Phi$ is the wave function of the $\pi$ meson.

However this Lagrangian is not invariant under rotations in isotopic spin space. Consequently it is possible in principle to verify the K-particle doublet hypothesis by studying the universality of isotopic invariance in strong interactions and the existence of a strong $KK\pi$ interaction. (In this connection we should mention the work of Taylor[11] in which very general considerations based on a method of Chew[12] are used to show, by comparing the theory with the experimental results on the production of strange particles, that a strong $KK\pi$ interaction is necessary.) It is true that one must keep in mind the hypothesis advanced by Pais[13,14] according to which the $K^+$ and $K^0$ mesons have opposite parity. Here there are two possibilities: the $KK\pi$ interaction conserves parity but isotopic invariance is violated,[13] or the alternative — isotopic spin is conserved but parity conservation is violated.[14]

It is seen that the question of K-meson doublets can hardly be solved in the framework discussed above. A real possibility for verifying the parity doublets hypothesis will be indicated below.

Before passing on to a study of the consequences of the hypothesis of strange particle doubling on the processes of their interaction and production we note the following circumstance.

The revival in this paper of the parity doublets hypothesis is connected with the fact that, as will be seen later, the existence of a "forward-backward" ("right-left") asymmetry in processes involving strange particles may be explained not only by giving up space parity conservation in strong interactions of strange particles but also on the basis of the above introduced hypothesis. Also it is possible to find experimental tests to determine whether the "forward-backward" ("right-left") asymmetry in processes involving $\Lambda$ and $\Sigma$ particles is due to parity nonconservation in strong interactions or not.

## 3. INTERACTION AND PRODUCTION OF STRANGE PARTICLES

Turning now to effects resulting from the hypothesis discussed above we use the notation of Lee and Yang.[9]

Let us consider first the process of $K^-$-particle capture by protons leading to formation of $\Sigma^-$-hyperon doublets which subsequently decay, with the $K^-$ beam consisting of a coherent mixture of $\theta^-$ and $\tau^-$ particles with amplitudes $a_\theta$ and $a_\tau$. The density matrix describing the $\Sigma^-$-hyperon beam at the instant of production ($t = 0$) is given by

$$D(0) = \begin{pmatrix} I_1(0) + \mathbf{P}_1(0)\boldsymbol{\sigma} & J(0) + \mathfrak{P}_1(0)\boldsymbol{\sigma} \\ J^+(0) + \mathfrak{P}_2^+(0)\boldsymbol{\sigma} & I_2(0) + \mathbf{P}_2(0)\boldsymbol{\sigma} \end{pmatrix}. \tag{1}$$

The diagonal terms in Eq. (1) correspond to the usual density matrix for a beam of intensity I and polarization $\mathbf{P}$, the off-diagonal terms result from interference effects between the doublet components of opposite parity: J is a pseudoscalar, $\mathfrak{P}$ is a polar vector. The time dependence of these quantities is given by the exponential factor $e^{-\lambda t}$ where $\lambda^{-1}$ is the lifetime of the $\Sigma^-$ particles (it is the same for $\Sigma_1^-$ and $\Sigma_2^-$ in the model under consideration).

For the capture process $I_i$, $J_i$, $\mathbf{P}_i$ and $\mathfrak{P}_i$ are given by

$$I_1(0) \equiv I_1(t)|_{t=0} = |\alpha_\theta|^2 |a|^2 + |\alpha_\tau|^2 |b|^2,$$
$$I_2(0) = |\alpha_\theta|^2 |b|^2 + |\alpha_\tau|^2 |a|^2$$
$$J(0) = \alpha_\theta \alpha_\tau^+ |a|^2 + \alpha_\tau \alpha_\theta^+ |b|^2, \quad \mathbf{P}_1(0) = \mathrm{Re}\,[\alpha_\theta \alpha_\tau^+ ab^+]\,\mathbf{k}_\Sigma / k_\Sigma,$$
$$\mathbf{P}_2(0) = \mathrm{Re}\,[\alpha_\theta \alpha_\tau^+ ba^+]\,\mathbf{k}_\Sigma / k_\Sigma,$$
$$\mathfrak{P}(0) = [|\alpha_\theta|^2 ab^+ + |\alpha_\tau|^2 ba^+]\,\mathbf{k}_\Sigma / k_\Sigma, \tag{2}$$

where $\mathbf{k}_\Sigma$ is the momentum of the $\Sigma^-$ hyperon. In Eq. (2) a and b denote the amplitudes for the processes $\theta^- + p \to \Sigma_1^- + \pi^+$ ($\tau^- + p \to \Sigma_2^- + \pi^+$) and $\theta^- + p \to \Sigma_2^- + \pi^+$ ($\tau^- + p \to \Sigma_1^- + \pi^+$) respectively. These processes are dynamically different since they lead to final states with different orbital angular momenta, so that $a \neq b$.

The $\Sigma^-$-hyperon decay process is described by the column (cf. reference 9)

$$M = \begin{pmatrix} A_0 [1 + \varkappa \boldsymbol{\sigma} \mathbf{k}] \\ B_0 [\varkappa + \boldsymbol{\sigma} \mathbf{k}] \end{pmatrix}, \tag{3}$$

where $\kappa$ is the degree of parity nonconservation in the decay, and $\mathbf{k}$ is a unit vector along the direction of the decay nucleon (in the hyperon rest frame).* $A_0$ and $B_0$ are related to the probabilities $\lambda_i$ of the $\Sigma_1$ of the $\Sigma_2$ decay by

$$|A_0|^2[1+\varkappa^2]=\lambda_1, \qquad |B_0|^2[1+\varkappa^2]=\lambda_2. \tag{4}$$

(Of course, in our model expression (3) must commute with the parity conjugation operator $C_p$ so that $A_0 = \pm B_0$ and $\kappa = \pm 1$. However we find it convenient in the following to use this general notation for purposes of comparison and only to impose the above equalities in the final expressions.)

We obtain for the angular distribution of the nucleons relative to the direction of emission of the $\Sigma^-$ hyperons (in the hyperon rest frame):

$$W = \mathrm{Sp}\,(MDM^+) = N + Q\cos\theta, \tag{5}$$

$$N = \lambda[|a|^2+|b|^2]\,|\alpha_\theta+\alpha_\tau|^2,$$

$$Q = \pm\lambda[|\alpha_\theta|^2+|\alpha_\tau|^2+\mathrm{Re}\,\alpha_\theta\alpha_\tau^+]\,2\,\mathrm{Re}\,ab^+, \tag{5'}$$

where the upper sign corresponds to $\kappa = 1$ and the lower sign to $\kappa = -1$.

A characteristic of the "forward-backward" asymmetry formula obtained here, as distinct from the results of Lee and Yang,[9] is the coherence of the $\theta$ and $\tau$ particles in the $K^-$-capture process. This fact is obviously related to parity nonconservation in the act of decay.

The circumstance that no "forward-backward" asymmetry has been observed in $K^-$ captures may be explained by assuming that one of the amplitudes a, b is small in comparison with the other at energies of the order of the energy available in the $K^-$ capture process. Of course, neither here nor below do we obtain any changes in lifetime characteristic of the Lee and Yang work, since $\lambda_1 = \lambda_2 = \lambda$ and the masses of the components of the doublet are strictly equal.

Let us consider next production of $\Lambda$ and $\Sigma$ hyperons in $\pi$-N or N-N collisions. In this case, after "averaging" over all remaining particles involved in the reaction, we get[9]

$$I_1 = I_2 = I, \qquad \mathbf{P}_1 = \mathbf{P}_2 = \mu\mathbf{n}, \qquad J = 0,$$

$$\mathfrak{P} = \mathfrak{P}^+ = \nu_1\mathbf{k}_{\mathrm{inc}} + \nu_2\mathbf{k}_\Lambda, \tag{6}$$

where $\mathbf{P}_i$ are the usual polarization vectors, $\mathbf{n} = \mathbf{k}_{\mathrm{inc}} \times \mathbf{k}_\Lambda$; $\mu$, $\nu_1$, $\nu_2$ are constants depending on the dynamics of the process; $\mathbf{k}_{\mathrm{inc}}$ and $\mathbf{k}_\Lambda$ are unit vectors in the direction of the incident particle and of the hyperon in the center of mass system.

For the angular distribution of the decay nucleons in the rest frame of the hyperon we find the expression

$$W = [|A_0|^2+|B_0|^2]\,[(1+\varkappa^2)\,I + 2\varkappa\mu\mathbf{n}\mathbf{k}] + (1+\varkappa^2)\,2\,\mathrm{Re}\,A_0B_0^+(\nu_1\mathbf{k}_{\mathrm{inc}}+\nu_2\mathbf{k}_\Lambda)\,\mathbf{k}. \tag{7}$$

Here $\mathbf{k}$ is a unit vector in the direction of the nucleon momentum; we do not as yet consider our specific model and therefore use expression (3). This corresponds to the fact that parity nonconservation is not connected with the invariance of weak interactions under the $\theta \longleftrightarrow \tau$ conjugation.

The term proportional to $\kappa$ and intrinsically connected with parity nonconservation in the decay gives rise to the "up-down" asymmetry. The "forward-backward" ("right-left") asymmetry, expressed by the second term in (7) could also arise if parity were conserved in the decay process. In that case the "effective" asymmetry coefficients in the decay would be, generally speaking, different in the direction $\mathbf{n}$ and $\nu_1\mathbf{k}_{\mathrm{inc}} + \nu_2\mathbf{k}_\Lambda$. This is an example of the independence of effects due to parity nonconservation in the decay from those due to the parity doublets in the conventional treatment, as was pointed out in the past by Arnowitt and Teutsch.[15]

On the other hand, if parity is not conserved in the strange particle production process then the density matrix for the hyperon beam will have the following structure:*

$$I + \sigma\mathbf{P} + \sigma\mathfrak{P},$$

and for the decay $M = A_0(1+\kappa\sigma\mathbf{k})$.

For the corresponding angular distribution we find

$$W = |A_0|^2\,[I\,(1+\varkappa^2) + 2\varkappa\,(\mathbf{P}+\mathfrak{P})\,\mathbf{k}] \tag{8}$$

with the same asymmetry coefficients. However it is not difficult to see that Eq. (7) also gives equal asymmetry coefficients if we take into account the equalities $A_0 = \pm B_0$, $\kappa = \pm 1$, which hold in our approach. In that case

$$W = \lambda\,[I \pm (\mathbf{P}+\mathfrak{P})\,\mathbf{k}] \tag{9}$$

and the consequences due to parity nonconservation

*We assume here for simplicity that the degree of parity nonconservation $\varkappa$ is the same in the decay of $\Sigma_1$ and $\Sigma_2$, although from the invariance of expression (3) under the $\theta \to \tau$ conjugation one can deduce only that $\varkappa_1\varkappa_2 = 1$. This however does not affect results connected with maximal parity nonconservation in the decay when $\varkappa^2 = 1$.

*Let us note the difference in the formal apparatus in our case and in the case of parity nonconservation in strong interactions. In the latter case the density matrix for particles produced in strong interactions has on the diagonal pseudoscalar terms, whereas in our case the pseudoscalars appear only for the off-diagonal elements of the density matrix.

are the same as the consequences arising from our model.

Let us consider one more interesting example of a process involving strange particles*

$$\Sigma^0 + p \to \Lambda^0 + p, \tag{10}$$

in which the capture takes place from the S-state of the continuous spectrum. If parity is not conserved in this process the $\Lambda^0$ particle should be produced in S as well as P states, so that the transition amplitude has the form (compare reference 16):

$$a_1\Pi_t + a_2\Pi_s + \chi\,[({}^3/_2)^{1/2} b_1 \mathbf{k}_\Lambda \mathbf{S} + 3^{1/2} b_2 \mathbf{k}_\Lambda \mathbf{S}'\,\Pi_t + b_3 \mathbf{k}_\Lambda \cdot \mathbf{S}'\Pi_s], \tag{11}$$

where $a_i$ and $b_k$ are amplitudes for the $S \to S$ and $S \to P$ transitions respectively,

$$\Pi_t = \tfrac{1}{4}(3 + \sigma_1\sigma_2), \qquad \Pi_s = \tfrac{1}{4}(1 - \sigma_1\sigma_2),$$

$$\mathbf{S} = \tfrac{1}{2}(\sigma_1 + \sigma_2), \qquad \mathbf{S}' = \tfrac{1}{2}(\sigma_1 - \sigma_2),$$

and $\chi$ is the degree of parity nonconservation in the process (10). The subscript 1 in the spin matrices refers to the strange particles, subscript 2 to the proton. For the angular distribution of $\pi$ mesons from the $\Lambda^0$ decay we obtain the following expression:

$$W = \lambda I\,[\beta + 4\mathrm{Re}(\chi\alpha)\,\mathbf{k}_\pi \mathbf{k}_\Lambda \varkappa/(1 + \varkappa^2)], \tag{12}$$

where I is the intensity of the $\Sigma^0$ beam,

$$\alpha = \tfrac{1}{2}\,[\sqrt{{}^3/_2}\,a_1^+(b_1 + b_2/\sqrt{2}) + \tfrac{1}{2}\,a_2^+ b_3],$$

$$\beta = \tfrac{1}{4}\,[3\,|a_1|^2 + |a_2|^2 + 3\,|b_1|^2 + 9\,|b_2|^2 + 3\,|b_3|^2].$$

Let us now discuss the same process from the point of view of the parity doublets hypothesis advanced here. The density matrix of the incident $\Sigma^0$-hyperon beam consisting of $\Sigma_1^0$ and $\Sigma_2^0$ has the form (for hyperons of low kinetic energy):

$$\rho_i = \begin{pmatrix} I_1 & J \\ J^+ & I_2 \end{pmatrix}. \tag{13}$$

We assume, without loss of generality, that the relative parity of $\Sigma_1$ and $\Lambda_1$ is positive. Then the reaction corresponds to $S \to S$ transitions. and the existence of doublets of the $\Sigma$ and $\Lambda$ particles will result in the $S \to P$ transitions: $\Sigma_{1,2} + p \to \Lambda_{2,1} + p$. In this case the transition amplitude is in the form of a $2 \times 2$ matrix

$$\begin{pmatrix} S \to S & S \to P \\ S \to P & S \to S \end{pmatrix} \tag{14}$$

where $S \to S$, $S \to P$ represent symbolically the amplitudes of the corresponding transitions of the strange particle + proton system, taken from the work of Pais and Treiman.[16]

After some calculations we find for W the following expression:

$$W = \lambda\,\{[I \pm \mathrm{Re}\,J]\,\beta + 2\,\mathrm{Re}\,(I \pm J)\,\alpha \mathbf{k}_\pi \mathbf{k}_\Lambda\}, \tag{15}$$

where we have already set $\kappa = \pm 1$, as well as $I_1 = I_2 = I$.

*It is in this reaction that a nonvanishing "forward – backward" asymmetry of $\pi^-$ mesons from $\Lambda^0$ decay was observed, although the results are not definitive.

## 4. DISCUSSION OF RESULTS

From a comparison of (8) and (9) with (12) and (15) the conclusion follows that if parity nonconservation in the decay is the maximum possible (as is in agreement with experimental data) then the consequences due to parity nonconservation in the strong interactions of strange particles are the same, as far as production of particles with odd strangeness is concerned, as the consequences due to the hypothesis of invariance of all interactions under the $\theta \longleftrightarrow \tau$ conjugation.

The two approaches (should the "forward-backward" asymmetry be definitely proven) may, however, be distinguished by studying, for example, reactions producing $\Xi$ particles:

$$\pi^- + p \to \Xi^- + K^+ + K^0,$$
$$\pi^+ + n \to \Xi^- + K^+ + K^+. \tag{16}$$

If the "forward-backward" ("right-left") asymmetry in processes involving $\Lambda$ and $\Sigma$ particles is connected with invariance of the interactions under the $\theta \longleftrightarrow \tau$ conjugation then there should be no "forward-backward" ("right-left") asymmetry in the distribution of the $\Lambda^0$ particles ($\pi^-$ mesons) from the $\Xi^-$ decay because the $\Xi^-$ particle is not a parity doublet and consequently will have zero longitudinal polarization (in our model parity is conserved in strong interactions). If, however, the indicated asymmetry is due to parity nonconservation in the strange particle production process then the asymmetry of $\Lambda^0$ particles ($\pi^-$ mesons) from $\Xi^-$ decay will, generally speaking, be different from zero.

Indeed, in the framework of parity nonconservation for processes involving K mesons and hyperons, the reactions (16) may be caused by the following renormalizable parity-conserving interactions (we assume here for simplicity that the parity of all fermions and K mesons is positive);

$$g_6\,[\bar{N}\theta\Lambda + \bar{\Lambda}\theta^+ N], \qquad g_7\,[\bar{\Xi}\tau_2\theta^+\Lambda + \bar{\Lambda}\theta\tau_2\Xi]$$

and the following CP and charge-invariant but parity nonconserving interactions:

$$ig_6'\,[\bar{N}\gamma_5\Lambda\theta - \bar{\Lambda}\theta^+\gamma_5 N], \qquad ig_7'\,[\bar{\Xi}\gamma_5\tau_2\theta^+\Lambda + \bar{\Lambda}\theta\gamma_5\tau_2\Xi].$$

The effective matrix element for the process, including interferences between the interactions with primed and unprimed constants, will contain pseudoscalar terms and, generally speaking, the $\Xi^-$ particle will be longitudinally polarized.

The same conclusions follow from Sakata's[17] model in which the interaction $(\overline{\Lambda}\Lambda)(\overline{N}N)$ responsible for the production of strange particles of any strangeness does not, generally speaking, conserve parity.[7]

In connection with all that has been said a study of reactions of the type (16) becomes of great interest.

In conclusion we might venture the hypothesis that the various kinds of asymmetries of physical processes are not a consequence of an asymmetry of space but are due to specific properties of the neutrino and of the strange particles. It is possible that invariance of all interactions under the "$\theta$-$\tau$ conjugation" is a formal expression of some peculiar intrinsic properties of strange particles.

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