(1,2) state to $L_1(p,s)$, and we find that it differs from the kernel of reference 9 by a factor of $\{[E(s)+M]/[E(p)+M]\}^{\frac{1}{2}}$. This difference can be absorbed in the relation

$$f(p)=\{[E(p)+M]/[E(k)+M]\}^{\frac{1}{2}}G_0(p),$$

between $G(p)$ and the wave function $f(p)$ calculated in reference 9. If the wave function is needed only on the energy shell, then $f(k)=G_0(k)$. In a calculation which requires the high-momentum components of $G(p)$ (e.g., meson photoproduction), it is important to distinguish between $f(p)$ and $G_0(p)$.

PHYSICAL REVIEW VOLUME 104, NUMBER 4 NOVEMBER 15, 1956

Dynamical Theory of K Mesons

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
(Received June 18, 1956; added note received September 11, 1956)

Considerations leading to a complete dynamical theory of K particles and hyperons are outlined. The theory exploits several points of analogy between the π field and the electromagnetic field, and gives a qualitatively satisfactory description of a number of phenomena. In particular, it accounts for the variety of K-particle decay modes, including those exhibiting opposite parity.

ONE of the most striking characteristics of K particles[1] is their ability to exhibit either positive or negative intrinsic parity on decaying into π mesons, while displaying but a single lifetime and a single mass in all the varied decay modes accessible to charged K particles. This note contains a brief descriptive account of a dynamical theory of K mesons and hyperons that seems to provide an explanation for this behavior, as well as of other properties of these particles.

The concept[2] of a K meson as a Bose-Einstein (B.E.) particle carrying an isotopic spin of $\frac{1}{2}$ is now well supported experimentally. A fundamental aspect of isotopic spin $T=\frac{1}{2}$, which is common to the nucleon and the K meson, is emphasized through the description of particles by multicomponent Hermitian fields. Unlike $T=1$ where three components suffice, as in the proper isotopic vector characteristic of the π-meson field, an isotopic spin of $\frac{1}{2}$ requires 4 components for its representation. This is analogous to the situation with an ordinary spin, and similarly implies the existence of a second three-dimensional isotopic spin, which permits an interpretation in terms of a four-dimensional space. In order to construct the coupling between the Fermi-Dirac nucleons and the pseudoscalar π-meson field, however, a direction must be distinguished in the second three-dimensional isotopic spin space and four-dimensional symmetries do not exist. The additional invariance property that does occur, referring to rotations about the preferred axis, is analogous to that defining electrical charge Q and we speak of this property as nucleonic charge N, with $N=+1$ and -1 distinguishing nucleon and antinucleon. Thus, the assignment of an isotopic spin of $\frac{1}{2}$ to the nucleonic field leads automatically to the property of nucleonic charge, and opposite charges are distinguished physically by the coupling with the π field. It is now natural to suppose that the K meson, with isotopic spin $\frac{1}{2}$, possesses a similar physical property in the nature of a charge, which is also dynamically realized by a coupling with the π field. We shall term this new property hyper(onic) charge Y, with $Y=+1$ characterizing the K^+K^0 multiplet, and $Y=-1$ describing the antiparticles $\bar{K}^0K^-$. As the agent for the dynamical exhibition of nucleonic and hypercharge, the π field does not itself bear these charges. The slow disintegration of K particles into π mesons thus implies that, unlike electrical and nucleonic charge, hypercharge is not absolutely conserved. If the quanta of the K field are to be emitted and absorbed singly by Fermi-Dirac (F.D.) particles with nucleonic charge, the latter must also carry hypercharge. We shall associate hypercharge exclusively with $T=\frac{1}{2}$, and require that, in analogy with electrical and nucleonic charge, no multiply hypercharged fundamental particle exists. Then the simplest closed set of TY assignments is $T=\frac{1}{2}$, $Y=+1$; $T=\frac{1}{2}$, $Y=-1$; $T=0$, $Y=0$; $T=1$, $Y=0$, which for $N=+1$ we identify, respectively, with the multiplets comprising the nucleon, the Ξ particle, the Λ particle, and the Σ particle. The classification of the related antiparticles follows from the general symmetry operation of charge reflection, which simultaneously reverses all charges, N, Y, and $Q=T_3+\frac{1}{2}Y$. The interactions between these particles and the K mesons, subject to the conservation of hypercharge, obey selection rules which are precisely those that have been expressed by the empirical

[1] For the experimental information cited, see the *Proceedings of the Sixth Rochester Conference on High-Energy Physics, 1956.* Various proposals to account for the mass and lifetime properties of K particles are discussed here.

[2] M. Gell-Mann, Phys. Rev. **92**, 833 (1953); T. Nakano and K. Nishijima, Progr. Theoret. Phys. Japan **10**, 581 (1953).

"strangeness" number.[3] The connection is $S=Y-N$. Our viewpoint differs from the less specific strangeness concept in two respects. It corresponds to a definite field-dynamical scheme, with physical quantities and conservation laws related to invariance properties, and it suggests a limitation on the number of hyperons that seems consistent with present experience.

The idea, that hypercharge is analogous to nucleonic charge in being realized dynamically through interaction with the π field, receives some support from experiments on the angular distribution of K particles generated in $\pi^- - p$ collisions. By using a beam of 1.3-Bev π^- mesons, it has been observed that the K^0 particles produced in the reactions $\pi^- + p^+ \rightarrow K^0 + \Lambda^0$, Σ^0 exhibit a pronounced forward asymmetry in the center-of-mass system, while the angular distribution of K^+ particles, produced by $\pi^- + p^+ \rightarrow K^+ + \Sigma^-$, is comparatively isotropic and favors the backward direction. Let us remark first that if the reaction proceeds through the intermediate stage $\pi^- + p \rightarrow n$, the angular distribution should be relatively isotropic and would not discriminate particularly between K^+ and K^0 production. If we take into account the possibility of virtual proton dissociation into K-particles and hyperons, $p^+ \leftrightarrow K^+ + \Lambda^0$, Σ^0 and $p^+ \leftrightarrow K^0 + \Sigma^+$, the capture of the π^- meson by the hyperons would liberate either K^0 or K^+ with an angular distribution influenced by the backward motion of the proton in the center-of-mass system. A process of $\pi - K$ scattering followed by the capture of the π meson by a hyperon could account for the observed angular distributions, but not without further special assumptions. A striking distinction between K^0 and K^+ production appears automatically only if the K particle can absorb a π meson. Of the two varieties of K particles, K^+ and K^0, only K^+ can absorb π^-, and the resulting K^0 formed in association with Λ^0 or Σ^0 will be projected forward. Hence, angular distributions of the observed type should emerge in a natural way from the mechanisms of π capture by K particles,[4] and by nucleons and hyperons.

In remarkable contrast with these arguments for the hypothesis that K mesons possess an interaction with the π field that is analogous to the pion-nucleon coupling, there must now be placed the fact that K particles with a definite intrinsic parity and spin 0 (as the energy distributions in the 3π decay indicate) cannot interact in this manner with the pseudoscalar π field. Expressed in terms of a spin 0 field ϕ_K, and omitting the necessary isotopic spin matrices, this assertion is simply the observation that $\phi_K\phi_K$ is necessarily a scalar and cannot be a pseudoscalar. Then, if we insist upon a coupling of the form $\phi_\pi\phi_K\phi_K$, we can only conclude that the intrinsic parity of the K particle is a dynamical quantity capable of assuming either value, $+1$ or -1. On decomposing the K field into parts with definite intrinsic parity, the desired interaction is obtained as $\phi_\pi\phi_{K+}\phi_{K-}$. Thus, K particles that can exhibit either intrinsic parity are an inevitable consequence of the line of thought leading to hypercharge and its dynamical manifestations. The manner in which the two parity values will be revealed is also dominated by the strong π coupling. In view of the rapid K-parity fluctuation implied by this interaction, ϕ_{K+} and ϕ_{K-} are not the proper basis for the description of K particles. Rather, we must introduce the fields

$$\phi_{K1}=2^{-\frac{1}{2}}(\phi_{K+}+\phi_{K-}),\quad \phi_{K2}=2^{-\frac{1}{2}}(\phi_{K+}-\phi_{K-}),$$

which are such that the π coupling

$$\phi_\pi\phi_{K+}\phi_{K-}=\tfrac{1}{2}[\phi_\pi\phi_{K1}\phi_{K1}-\phi_\pi\phi_{K2}\phi_{K2}]$$

does not imply a transition from one kind of K particle to another. Hence the observed K particles, which are produced in regions occupied by intense π fields, must be K_1 or K_2, with an accompanying π field. These are mixtures, with equal amplitude and either phase, of systems with opposite parity. The two types of K particles are distinguished by the coupling with the π field, but in view of the symmetry operation $\phi_{K1}\leftrightarrow\phi_{K2}$, $\phi_\pi \rightarrow -\phi_\pi$, there will be no observable difference in the absence of an externally generated π field. In particular the masses of K_1 and K_2 will be identical. Furthermore these particles will exhibit a mean lifetime for decay which, apart from a difference between electrically neutral and charged K particles, is identical for K_1 and K_2 and is common to all competing modes of disintegration.[5] The latter properties depend upon the weakness of the interactions responsible for disintegration, in comparison with the pion and electromagnetic couplings that characterize a K meson of given charges Y and Q. Thus, the reciprocal lifetime of a K particle will be given by the additive contributions of the various decay modes, which can manifest either value of intrinsic parity since both are represented in the $K_{1,2}$ particles. In virtue of the independent operation of the even- and odd-parity decay mechanisms, there can be no difference between the K_1 and K_2 lifetimes. And, from the requirement of charge symmetry it follows that this common lifetime can depend only upon $|Q|$. An example of such dependence is provided by the simplest mechanism of decay, the spontaneous disappearance of a quantum of the K field in conformity with the exact conservation laws. The coupling with the π field converts this virtual process into a physical decay of the K particle yielding 2 or 3 π mesons, the θ and τ decay modes. The relatively small kinetic energy available in

[3] K. Nishijima, Progr. Theoret. Phys. Japan **12**, 107 (1954); M. Gell-Mann and A. Pais, *Proceedings of the Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, London, 1955), reference 1.

[4] I am indebted to M. Goldhaber for calling my attention to his discussion of the possible connection between the K^0 angular distribution and a $K-\pi$ interaction: M. Goldhaber, Phys. Rev. **101**, 433 (1956).

[5] This statement requires an important qualification; the decay of K_1 and K_2 could be a more complicated function of time than a simple exponential. See the added note at the end of the paper. I am grateful to a number of people for expressing doubt concerning the assertion of a single lifetime.

3π decay is not favorable to the τ modes, and since the $\theta^{\pm}$ modes also depend upon the existence of electromagnetic interactions, the θ^0 mechanism should be most effective. Hence a shorter lifetime for the neutral K particles is anticipated, in agreement with experiment.

The preceding considerations emphasize analogies between the photon field and the π field that appear to be deeper than the similarities upon which Yukawa founded the meson theory. Apart from the special aspects of the electromagnetic field that stem from its vector nature and the zero mass of the photon, the two fields are alike in being B.E. fields that are coupled both to F.D. and to B.E. particles, and in being the physical basis for defining properties of these particles that have the characteristics of charge. Now it is familiar that current theory ascribes to electromagnetic interactions a further role; it is considered that, in a hypothetical universe without electromagnetic couplings, the approximate degeneracy of mass multiplets ($p-n$, $\pi^{\pm}-\pi^0$) would be exact. That is, the three-dimensional isotopic spin space of internal symmetry operations is fully meaningful in the absence of electromagnetic interactions, whereas the action of the latter effectively reduces the dimensionality of this space. We are naturally led to inquire whether the π-photon analogy extends to this aspect of electromagnetic interactions. Is it possible that, in an idealization where some or all of the π couplings are removed, further degeneracies and symmetries will come into view that are now obscured by the effects of strong interactions? An indication in this direction comes from the suggestion that nucleonic and hyperonic charge are equally effective in π coupling when they reside on the same $T=\frac{1}{2}$ particle, which is to say that $\frac{1}{2}(N+Y)$ is the relevant charge. On this basis we would assert that the fundamental distinction between N and Ξ is that the nucleon is directly coupled to the π field while the Ξ particle is not. Now, a linear coupling between and a B.E. field and a F.D. field will decrease the observed mass of the F.D. particle if virtual processes that reverse the parity of the F.D. particles are not too significant. From some evidence that this may be the situation in $\pi-N$ coupling (weak s-scattering) we draw the tentative conclusion that the large difference between the observed masses of the nucleon and of the Ξ particle ($m_N=6.7$, $m_\Xi=9.4$, in units of the $\pi^{\pm}$ mass) is a consequence of the strong coupling of the π field to the nucleon, and that were this interaction to be removed, N and Ξ would become a degenerate $N=1$, $T=\frac{1}{2}$ multiplet.

Continuing in the same spirit, we assert that the mass difference between Λ and Σ ($m_\Lambda=8.0$, $m_\Sigma=8.5$) can be ascribed to an indirect effect of the $\pi-K$ interaction. As a result of the two kinds of π couplings, there would exist between nucleons and K particles an interaction bearing some resemblance to nuclear interactions and, in particular, being strongly dependent upon the total isotopic spin. Indeed, this Yukawa type interaction should be largely responsible for the observed scattering of K^+ mesons by protons. And now, through the reactions $\Lambda\leftrightarrow N+\bar{K}$, $\Sigma\leftrightarrow N+\bar{K}$, and the T-dependent K-nucleon interaction, there would be produced mass displacements which, according to elementary considerations, act to depress the Λ ($T=0$) mass relative to that of Σ ($T=1$). Accordingly, we take the position that Λ and Σ would form a degenerate multiplet in a hypothetical situation without $\pi-K$ coupling. It is the latter degeneracy, with its coincidence of $T=0$ and $T=1$ states, that indicates the underlying symmetry which the strong π couplings distort; the internal symmetry space is a four-dimensional Euclidean manifold which is reduced to the aspect of the three-dimensional isotopic spin space through the operation of the π interactions. The requirement of four-dimensional invariance can be imposed upon the linear K-field coupling that describes the transfer of hypercharge between the B.E. K particles and the heavy F.D. particles. In consequence, the four interactions $KN\Lambda$, $KN\Sigma$, $K\Xi\Lambda$, $K\Xi\Sigma$ are united into a single structure characterized by one coupling constant, g_K. Thus, apart from the very weak effects that destroy hypercharge, this theory is symbolized by the interaction parameters g_K, $g_{\pi K}$, $g_{\pi N}$, and e.[6] It is to be noted that the dynamical intrinsic parity of the K particle must have a counterpart in the F.D. particles to which it is coupled. We shall assume that a variable intrinsic parity is characteristic of hyperonic and nucleonic charge in such a way that it is manifested for a particle carrying either type of charge, but is not when both are present. On this basis the K particle is linked with Λ and Σ through the invariance operations specific to intrinsic parity and, corresponding to K_1 and K_2, there would be two varieties of hyperons, $\Lambda_1\Sigma_1$ and $\Lambda_2\Sigma_2$, with generally identical properties.

At the stage in which the four-dimensional internal symmetries are fully evident, where only g_K differs from zero, the nucleo-hyperons form two distinct multiplets, one with half-integral T (1/2) and the other with integral T (0,1). The linear K coupling would itself produce such a mass splitting, and we are finally led to conjecture that, in the absence of all interactions, the heavy F.D. particles coalesce into a supermultiplet with a unique mass. It is also conceivable that the heavy B.E. particles originate from such a supermultiplet. Linear couplings between B.E. fields and F.D. particles depress the mass of the B.E. particle and, if the $\pi-N$ coupling predominates sufficiently over the other interactions, the observed mass spectrum could emerge. One might speculate here on the existence of a $T=0$ partner to the $T=1$ π field. However, since the dynamical introduction of the π field must upset the four-dimensional symmetry

[6] It might be noted here that fundamental electromagnetic interactions of the magnetic moment (Pauli) type appear to be excluded by considerations of relativistic invariance. The circumstances are peculiar to the electromagnetic field where a Lorentz transformation induces an operator gauge transformation. The operator character of the gauge transformation demands a test of consistency with the formally gauge-covariant field equations, which test fails if magnetic moment couplings are operative.

that stimulates this suggestion, there does not seem to be any compelling reason for postulating this unobserved particle.

There emerges from these various considerations an essentially well-defined theory of the interactions of heavy F.D. and B.E. particles among themselves and with the electromagnetic field. This theory is still incomplete, however, since it omits the apparently weak dynamical phenomena that involve the light F.D. particles, muon, electron, and neutrino. It also lacks a satisfactory understanding of the mechanisms that produce the slow decay of K particles and hyperons, with the emission of π mesons. In seeking some unity among these weak couplings, it is well to recognize that any underlying symmetry may be seriously distorted by the quite different strong interactions to which the various heavy particles are subjected. A kind of order, in this sense, does seem to appear if one disregards processes involving the mysterious electron. Thus, charged π mesons and charged K mesons disintegrate into $\mu+\nu$ with closely comparable decay rates, which we consider meaningful in view of the argument for the origin of π and K in a common multiplet. Presumably the different interaction properties of the particles must be invoked to account for the fact that the decay rates are so similar, despite the rather disproportionate energy releases in the two reactions. The variable internal parity of the K meson may be of importance in relating the null mass of the neutrino to an invariance requirement; only for zero mass can the dynamical properties of the neutrino field be preserved under the substitution $\psi_\nu \to \gamma_5\psi_\nu$, which is a parity reflection operation. It is natural to suppose that the charged meson coupling with μ and ν has a neutral analog of comparable strength involving μ and $\bar{\mu}$, or alternativly a neutrino pair. A decay of the type $K^0 \to \mu^+ + \mu^-$, occurring at a rate similar to that of $K^\pm \to \mu^\pm + \nu$, would not seem to be excluded by available evidence. Now a scalar coupling between neutral K particles and the μ field has an important property: the vacuum expectation value of the scalar constructed bilinearly from the μ field is not zero, and indeed is divergent according to present theory. On limiting the nonconvergent contributions of virtual μ pairs, we are presented with a phenomenon which could be described as the annihilation of a neutral, charge-symmetric, positive-parity K quantum with zero energy and momentum. As we have already mentioned, the $K-\pi$ coupling (and more indirectly, the $N-\pi$ coupling) converts this process into the physical one of K-particle disintegration into π mesons.[7] Since the decay of K^0, presumably through this mechanism, proceeds much more rapidly than the process producing $\mu+\nu$ from charged K particles, it appears that the contributions of the virtual μ pairs are described correctly by present theory up to fairly high energies.

This explanation of K-particle disintegration also accounts for the existence of hyperon decays involving the emission of single π mesons, and, from a consideration of the two couplings that can produce π mesons, one obtains a qualitative understanding of the relative lifetimes of the various hyperons. Consider, for illustration, the difference between Σ^+ and Σ^-. The effect of the g_K coupling is to produce the reactions $\Sigma^+ \leftrightarrow \bar{K}^0 + p$, $\Sigma^- \leftrightarrow K^- + n$. For Σ^+, the disappearance of the neutral K particle, combined with the production of a π^+ or π^0 meson by the proton, will be the dominant process. But in Σ^-, the negative K meson must first transform into a neutral K particle, $K^- \to \bar{K}^0 + \pi^-$, before the decay mechanism can operate. Accordingly, π^- emission from Σ^- proceeds through the $g_{\pi K}$ coupling, in contrast with the stronger $g_{\pi N}$ coupling primarily responsible for Σ^+ decay. We thus expect a longer lifetime for Σ^- in comparison with Σ^+, and one more similar to that of $\Lambda^0(\leftrightarrow \bar{K}^0 + n, K^- + p)$, where the two π couplings should be roughly commensurate in importance, since the smaller kinetic energy available to the π mesons in the latter situation tends to inhibit the p-state production associated with $g_{\pi N}$. The decay of $\Xi^-(\leftrightarrow K^- + \Lambda^0)$ resembles that of Σ^- in its dependence upon the $g_{\pi K}$ coupling and its lifetime should be of the same order of magnitude as those of Σ^- and Λ^0. In the general possibility of relating the lifetime variations to the available energy, and to the operation of the π-production mechanisms, we find an indirect confirmation of the underlying four-dimensional symmetry that is expressed by the single coupling constant g_K.

It appears that all of the significant decay modes of the hyperons and the mesons (apart from π^0) could have a common origin in a weak interaction of the B.E. particles with the μ, ν field.[8] That leaves only the comparatively improbable K-particle decay mode: $K \to \pi + e + \nu$, to which we might add the other well-known processes involving electrons, $\mu \to \nu + e + \nu$ and $n \to p + e + \nu$. It has become customary to suppose that the F.D. fields μ, ν and e, ν are interchangeable in these weak interactions. But it is difficult to ignore the striking dissimilarities between them; $\pi \to e + \nu$ is not observed, and although $K \to \pi^0 + e + \nu$ does occur, the two-body decay $K \to e + \nu$ seems to be unlikely. Accordingly, we shall conclude that the μ, ν and e, ν fields are associated with different types of interactions, the muon being coupled to heavy B.E. particles and the electron to F.D. fields, in the manner of the Fermi β-decay interaction.[9] The latter could be a general coupling in that it applies to all pairs of electrically charged and neutral F.D. fields with the same nucleonic charge, but it is specifi-

[7] The $K-\pi$ coupling, in conjunction with the μ, ν interaction, will also produce the three-body decay: $K^\pm \to \pi^0 + \mu^\pm + \nu$. Some of the detailed consequences of an elementary treatment of these decay processes seem to be satisfactory. Thus, in the τ decay mode, $K^+ \to 2\pi^+ + \pi^-$, the energy distribution of the π^- has an appreciable asymmetry about the average energy, with a preference toward higher energy.

[8] We also interpret μ capture by nucleons as an indirect effect of this interaction.

[9] The hope persists, of course, that this interaction can be ascribed to some coupling of the e, ν field with a boson field.

cally not the commonly assumed universal Fermi interaction, which implies processes other than β decay. If the mixed scalar and tensor coupling predominant in nuclear β decay is generally applicable, the pion decay $\pi\rightarrow e+\nu$, proceeding through virtual nucleon pairs, is forbidden. Although this would not be true of the corresponding radiative decay, $\pi\rightarrow\gamma+e+\nu$, the unfavorable nature of the three-body decay into light particles and the dependence upon the electromagnetic coupling, combined with the inference from the somewhat analogous process $\pi^0\rightarrow\gamma+\gamma$ that a perturbation treatment of the nucleon pairs overestimates the decay rate, all indicate that this decay mode should be below the present level of observability. In contrast with the problem of pion β decay, which is to reconcile its experimental absence with the implications of known interactions, the β-decay properties of the K meson call for the invention of a suitable hyperon β-decay coupling. As an illustration, one can exploit the dynamical intrinsic parity of Λ and Σ to forbid $K\rightarrow e+\nu$ while permitting the three-body decay $K\rightarrow\pi+e+\nu$. The K particle is strongly coupled with various pairs of nucleons and hyperons ($K^+\leftrightarrow p+\bar{\Lambda}^0$, $\Lambda^0+\bar{\Xi}^+$, $n+\bar{\Sigma}^+$, $\Sigma^++\bar{\Xi}^0$) in which, for example, ϕ_{K-} is combined through a scalar coupling with $\psi_{\Lambda-}$. Now suppose that the mixed scalar and tensor β-decay interaction producing $\bar{\Lambda}^0\rightarrow\bar{p}+e^++\nu$ involves $\gamma_5\psi_{\Lambda-}$. Then the two-body β decay $K^+\rightarrow e^++\nu$ would be forbidden, whereas, through the intervention of the pseudoscalar $\pi-N$ coupling, the three-body decay $K^+\rightarrow\pi^0+e^++\nu$ could occur. The decay rate observed for the latter process is not inconsistent with this picture.

The ideas outlined here seem to be useful in supplying a qualitative understanding of various aspects of K particle and hyperon phenomena. But a quantitative test of these concepts will require a substantial development in the practical techniques of evaluating the implications of strongly coupled fields. Nor would that be enough, since this theory, being a field theory based on ordinary space-time description, is fundamentally inconsistent in its characterization of interactions within arbitrarily small space-time regions. Perhaps the intensification of such basic difficulties by this extension of conventional field concepts into the new high-energy domains of physics will aid in the eventual construction of a consistent foundation for the theory of elementary particles.

ADDED NOTE[10]

Some of the statements concerning K particle and hyperon decays require important qualifications, owing to insufficient recognition of the distinction between the particle concepts that are applicable at creation, and at disintegration. The point at issue is the relation of the designation of K particles as K_1 and K_2 to the equally valid complementary designation as K_+, K_-, where the various single-particle states are connected by

$$\sqrt{2}|K_1\rangle=|K_+\rangle+|K_-\rangle,$$
$$\sqrt{2}|K_2\rangle=|K_+\rangle-|K_-\rangle.$$

The states $|K_+\rangle$ and $|K_-\rangle$ are associated with definite intrinsic parity, while $|K_1\rangle$ and $|K_2\rangle$ are the eigenstates of the parity reflection operation R_p: $\phi_{K+}\leftrightarrow\phi_{K-}$. The hyperons Λ and Σ can similarly be described either in terms of intrinsic parity eigenstates or by eigenstates of parity reflection. In the production of K particles and hyperons, as in the reactions $\pi+p\rightarrow K+\Lambda$, $K+\Sigma$, the initial state is unaffected by the parity reflection operation, so that the final state must be characterized by the eigenvalue $+1$ of the operator R_p. Hence, in the associated production of K and Λ, for example, the final state is a linear combination of $|K_1\Lambda_1\rangle$ and $|K_2\Lambda_2\rangle$. Since the individual particles $K_{1,2}$, $\Lambda_{1,2}$, and $\Sigma_{1,2}$ retain their identity in subsequent scattering interactions with matter, we assert that these are the proper designations for the particles produced in energetic collisions of pions and nucleons.

The utility of the $K_{1,2}$ description depends upon the validity of the symmetry property R_p. As long as one disregards the decay processes this symmetry is exact, and the distinction between an isolated K_1 or K_2 particle refers to an internal degree of freedom that does not affect external characteristics such as the mass. This would continue to be true for a disintegration mechanism that maintained the intrinsic parity symmetry, and we could then assert that K_1 and K_2 had a common lifetime. If decay modes are characterized by definite parities, however, the exact validity of R_p is destroyed and $|K_1\rangle$, $|K_2\rangle$ are no longer true eigenstates. But the states of definite intrinsic parity continue to be meaningful, and the degeneracy of these states is removed by the action of the decay mechanisms. Thus the particles K_+ and K_- can have different lifetimes and slightly different masses. Since the states $|K_\pm\rangle$ are contained in $|K_{1,2}\rangle$ with equal amplitude we conclude that, for the description of decay processes, a K particle is to be viewed as an equiprobability mixture of the particles K_+ and K_-.

The various decay modes of charged K mesons appear to be characterized by a single lifetime, within fairly wide experimental limits, which suggests that the dominant decay process, $K\rightarrow\mu+\nu$ maintains the parity reflection symmetry. We have already remarked on just this possibility in connection with the zero neutrino mass.[11] The significant decay modes of K_+ are then $\mu+\nu$, $\pi+\mu+\nu$, 2π while those of K_- are $\mu+\nu$, $\pi+\mu+\nu$, 3π, $\pi+e+\nu$, where the last assignment follows from our discussion of β processes.[12] The decay rates of K_+ and

[10] The work reported in this added note was done at Stanford University, Stanford, California. I am very grateful for the hospitality accorded me.

[11] A similar comment has recently been published by S. A. Bludman, Phys. Rev. **102**, 1420 (1956).

[12] It might be noted that the two body β-decay $K_+\rightarrow e+\nu$ should not be completely forbidden, since the π^0 meson emitted in $K_-\rightarrow\pi^0+e+\nu$ could be reabsorbed by K_- to form K_+.

K_- are given by

$$w_+ = 1/\tau_+ = w_\mu + w_{2\pi},$$
$$w_- = 1/\tau_- = w_\mu + w_{3\pi+e},$$

while the branching ratios measured for a beam that has run for a (proper) time t from its point of creation are

$$p_{2\pi} = \frac{w_{2\pi}}{w_+}\left(\frac{e^{-t/\tau_+}}{e^{-t/\tau_+}+e^{-t/\tau_-}}\right),$$

$$p_{3\pi+e} = \frac{w_{3\pi+e}}{w_-}\left(\frac{e^{-t/\tau_-}}{e^{-t/\tau_+}+e^{-t/\tau_-}}\right).$$

If it happened that $w_{2\pi}=w_{3\pi+e}$, the lifetimes τ_+ and τ_- would be equal, and the branching ratios $p_{2\pi}$ and $p_{3\pi+e}$ would also be equal and independent of t. But if $w_{2\pi}>w_{3\pi+e}$, we should have $\tau_+<\tau_-$ and $p_{2\pi}>p_{3\pi+e}$, for small t. With increasing t the latter situation reverses, as the K_+ particles become depleted in comparison with K_-. The experimental situation[1] is not yet entirely well defined, although the present weight of evidence does suggest that $p_{2\pi}>p_{3\pi+e}$. A possible set of values for small t is $p_{2\pi}(0)=0.23$, $p_{3\pi+e}(0)=0.14$, which implies that

$$\frac{\tau_-}{\tau_+} = \frac{1-2p_{3\pi+e}(0)}{1-2p_{2\pi}(0)} = \frac{4}{3}.$$

The 2π decay will exhibit the lifetime τ_+, the 3π, $\pi+e+\nu$ modes the lifetime τ_-, while the μ-decay processes will appear with a mixture of the two lifetimes. The mean lifetime of the μ decays, measured for small t, would be $(\tau_+^2+\tau_-^2)/(\tau_++\tau_-)$, and choosing this as 1.2×10^{-8} sec we obtain $\tau_+=1.0\times10^{-8}$ sec, $\tau_-=1.3\times10^{-8}$ sec. This lifetime difference is not inconsistent with present evidence nor is the implication that the branching ratios change with varying t. Thus, if $t=2\tau_+=2.0\times10^{-8}$ sec, we expect that $p_{2\pi}=0.18$, $p_{3\pi+e}=0.17$. Evidently it would be instructive to measure the composition of a K beam that has traveled for an appreciable number of mean lifetimes.

The decay modes of neutral K particles are distinguished by parity and by charge symmetry. The connection between the single-particle states of definite hypercharge and the states classified by charge symmetry can be written

$$\sqrt{2}|K^0\rangle = |K^s\rangle + |K^a\rangle,$$
$$\sqrt{2}|\bar{K}^0\rangle = |K^s\rangle - |K^a\rangle.$$

Hence,

$$2|K_1^0\rangle = |K_+^s\rangle + |K_+^a\rangle + |K_-^s\rangle + |K_-^a\rangle$$

and

$$2|K_2^0\rangle = |K_+^s\rangle + |K_+^a\rangle - |K_-^s\rangle - |K_-^a\rangle,$$

while the analogous single-particle states of $\bar{K}^0$ are obtained by reversing the sign of $|K_\pm^a\rangle$. Neither parity symmetry nor hypercharge retains its significance when the decay mechanisms are considered, whereas parity and charge symmetry are exact concepts. Accordingly, in describing decay processes a neutral K particle is to be considered as an equiprobability mixture of the four particles K_+^s, K_+^a, K_-^s, K_-^a, which could have different lifetimes and slightly differing masses. The decay mechanism we have previously described, in which a neutral, charge-symmetric, positive-parity quantum of the K-field disappears spontaneously, will produce 2π decay of the K_+^s particle and 3π decay of K_-^s. And, through the additional action of the electromagnetic coupling, K_+^a and K_-^a will decay into $2\pi+\gamma$ and $3\pi+\gamma$, respectively. Decays into $\pi+\mu+\nu$ are equally significant for all four particles since the $\mu\nu$ coupling maintains parity symmetry while the distinct nature of the oppositely charged particles does not emphasize any particular charge symmetry. The latter feature also applies to decays of the type $\pi+e+\nu$, although these processes occur only for the odd-parity particles. Of the four lifetimes, it is τ_+^s that is to be identified with the observed short lifetime of 10^{-10} sec, while the other three, associated with "anomalous" K^0 decays, should be considerably longer. Thus, only $\frac{1}{4}$ of the neutral K particles decay rapidly.

The distinction in lifetime between K^s and K^a particles has been recognized previously,[13] and an experiment has been proposed[14] to demonstrate the possibility of regenerating fast decaying K^0 particles. From the present viewpoint we should describe the basis of this experiment in the following way. A beam of $K_{1,2}^0$ particles is produced and allowed to travel for a time that is long compared with τ_+^s but short in comparison with the other three lifetimes. Through this lapse of time, the states

$$|K_{1,2}^0\rangle = \tfrac{1}{2}|K_+^s\rangle + \tfrac{1}{2}|K_+^a\rangle \pm 1/\sqrt{2}\,|K_-^0\rangle$$

become (omitting common time factors)

$$\tfrac{1}{2}|K_+^a\rangle \pm 1/\sqrt{2}\,|K_-^0\rangle = 1/2\sqrt{2}\,|K_+^0\rangle - 1/2\sqrt{2}\,|\bar{K}_+^0\rangle \pm 1/\sqrt{2}\,|K_-^0\rangle.$$

If now the beam penetrates through an absorber that is thick enough to remove all the $\bar{K}^0$ particles but is sufficiently thin that no appreciable scattering occurs, the states are transformed into

$$1/2\sqrt{2}\,|K_+^0\rangle \pm 1/\sqrt{2}\,|K_-^0\rangle = \tfrac{1}{4}|K_+^s\rangle + \tfrac{1}{4}|K_+^a\rangle \pm 1/\sqrt{2}\,|K_-^0\rangle.$$

Hence the intensity of regenerated K_+^s particles is $\frac{1}{16}$, as compared with $\frac{1}{4}$ in the initial beam, and, apart from the geometrical reduction of intensity, one should find $\frac{1}{4}$ as many θ^0 decays after the absorber as appear near the target in which the K^0 particles are produced. Another type of regeneration should also exist, in which the K_-^0 particles produce K_+^s particles on scattering, preferably in hydrogenous materials.

That only $\frac{1}{4}$ of the K^0 particles decay rapidly is particularly significant for observations on the as-

[13] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955).
[14] A. Pais and O. Piccioni, Phys. Rev. **100**, 1487 (1955).

sociated production of neutral particles with techniques that discriminate against long-lived particles. In the reaction $\pi^-+p\rightarrow K^0+\Lambda^0$, for example, the final state of an otherwise completely specified collision is expressed by

$$\alpha_1|K_1{}^0\Lambda_1\rangle+\alpha_2|K_2{}^0\Lambda_2\rangle=\tfrac{1}{2}(\alpha_1+\alpha_2)(|K_+{}^0\Lambda_+\rangle+|K_-{}^0\Lambda_-\rangle)+\tfrac{1}{2}(\alpha_1-\alpha_2)(|K_+{}^0\Lambda_-\rangle+|K_-{}^0\Lambda_+\rangle),$$

where

$$|\alpha_1|^2+|\alpha_2|^2=\tfrac{1}{2}|\alpha_1+\alpha_2|^2+\tfrac{1}{2}|\alpha_1-\alpha_2|^2=1.$$

The part that contains the rapidly decaying $K_+{}^s$ particles is

$$2^{-\frac{3}{2}}(\alpha_1+\alpha_2)|K_+{}^s\Lambda_+\rangle+2^{-\frac{3}{2}}(\alpha_1-\alpha_2)|K_+{}^s\Lambda_-\rangle$$

and the corresponding probability is indeed $\frac{1}{4}$. However, this is not the only consideration that enters in the comparison with experiment. One must also take into account the probability that the $K_+{}^s$ decay goes through the θ^0 $(\pi^++\pi^-)$ mode and thus is visible, in contrast with the $2\pi^0$ decay mode. According to the branching ratio of 2:1, characteristic of the $T=0$ final state,[15] this probability is $\frac{2}{3}$. The same visibility factor applies to the Λ^0 decay $(p+\pi^-:n+\pi^0=2:1)$ where the final state is characterized by $T=\frac{1}{2}$. Also, we must recognize that the Λ^0 decay should exhibit two lifetimes, corresponding to the particles $\Lambda_+{}^0$ and $\Lambda_-{}^0$. This presents us with the alternative of viewing the single observed lifetime either as an approximately equal lifetime for the two varieties, or as the shorter of two significantly different lifetimes. In the first situation, the probabilities of seeing a Λ^0 decay (p_Λ), of seeing a K^0 decay (p_K), and of observing both decays simultaneously $(p_{\Lambda K})$, stand in the ratios $p_\Lambda:p_K:p_{\Lambda K}=1:\frac{1}{4}:\frac{1}{6}$ where $p_\Lambda=\frac{2}{3}$. By comparison, if one of the Λ lifetimes, say that of Λ_-, is sufficiently long that the decay of this particle would not be observed, the various probabilities are related by $p_\Lambda:p_K:p_{\Lambda K}=1:\frac{1}{2}:\frac{1}{6}|\alpha_1+\alpha_2|^2$, with $p_\Lambda=\frac{1}{3}$. It can be expected that $\frac{1}{6}|\alpha_1+\alpha_2|^2$ will vary with energy and angle, its maximum possible value being $\frac{1}{3}$. When the latter is attained, K_+ particles are produced only in association with Λ_+ particles. If it is Λ_- that has the short lifetime, $\alpha_1-\alpha_2$ would replace $\alpha_1+\alpha_2$, and the maximum value of $\frac{1}{3}$ for $\frac{1}{6}|\alpha_1-\alpha_2|^2$ corresponds to K_+ particles being produced only in association with Λ_-. On the reasonable assumption that the more rapidly decaying particles are preferentially produced together, in $\pi-p$ collisions, we should anticipate in either situation that the average value of $\frac{1}{6}|\alpha_1\pm\alpha_2|^2$ was not far below $\frac{1}{3}$. This is consistent with various measurements[1] of the probability that a K decay be visible when a Λ decay has been observed, which lends some support to the interpretation in terms of two distinct lifetimes for Λ.

A more detailed picture follows from our discussion of the angular distribution in the reaction $\pi^-+p\rightarrow K^0+\Lambda^0$, according to which the forward production of K^0 is ascribed predominantly to the absorption of the π^- by K^+ particles $(p\leftrightarrow K^++\Lambda^0)$. Since the latter process reverses the intrinsic parity of the K particle, the forward part of the angular distribution, and the relatively isotropic background, can be associated separately with the two different combinations of states that are characterized by the amplitudes $\alpha_1+\alpha_2$ and $\alpha_1-\alpha_2$. It is the essentially isotropic portion that depends upon the absorption of π^- through the $g_{\pi N}$ interaction $(\pi^-+p\rightarrow n\rightarrow K^0+\Lambda^0)$, and the latter should be the π-production mechanism involved in the faster Λ decay. Hence, under the assumption that one lifetime is too long to contribute significantly, we should expect that the conditional probability $p_{\Lambda K}/p_\Lambda$ would be $\frac{1}{3}$ for K particles produced at a large angle relative to the incident beam, and would decrease as one approached the forward direction, corresponding to the increase of the differential cross section.

Some information about the long-lived neutral K-particle decay modes comes from the corresponding charged-particle modes. Thus on comparing $\pi^\pm+\mu^\mp+\nu$ decays with $\pi^0+\mu^++\nu$, and $\pi^\pm+e^\mp+\nu$ with $\pi^0+e^++\nu$, we infer the following partial decay rates:

$$\pi+\mu+\nu:\quad w_\pm{}^s=w_\pm{}^a=2w_{\pi^0+\mu},$$
$$\pi+e+\nu:\quad w_-{}^s=w_-{}^a=2w_e,$$

in which

$$w_{\pi^0+\mu}=2p_{\pi^0+\mu}(0)/(\tau_++\tau_-),\quad w_e=2p_e(0)/\tau_-.$$

For the 3π decay modes we find

$$3\pi:\quad w_-{}^s=w_{3\pi},\quad w_{3\pi}=2p_{3\pi}(0)/\tau_-,$$

and one should also note that, in contrast with the charged particle decay where the branching ratio of the alternative modes, $2\pi^++\pi^-$ and $2\pi^0+\pi^+$, is 4:1, the branching ratio of $\pi^++\pi^-+\pi^0$ and $3\pi^0$ is 2:3. Accordingly, the visibility factor of the neutral 3π decay is $\frac{2}{5}$. From the presently available measurements of charged K-particle lifetimes and branching ratios $[p_{\pi^0+\mu}=0.03,\ p_e=0.06,\ p_{3\pi}=0.08]$ we estimate that $2w_{\pi^0+\mu}=0.05\times10^8\ \mathrm{sec}^{-1}$, $2w_e=0.18\times10^8\ \mathrm{sec}^{-1}$, $w_{3\pi}=0.12\times10^8\ \mathrm{sec}^{-1}$. If the decay processes of a neutral K beam are observed in a small chamber, after a time of flight that is long compared with $\tau_+{}^s$ but short enough to maintain the numerical equality of the three long-lived components, the relative numbers of decays of various types will be proportional to the additively composed partial decay rates of the different species. Hence, on including the visibility factor of 3π decay, we should have $N_{\pi+\mu+\nu}:N_{\pi+e+\nu}:N_{3\pi}\simeq15:36:5$. Under such circumstances, then, the most probable decay mode is $\pi+e+\nu$, and 3π decay should be comparatively infrequent. These qualitative inferences appear to be in agreement with some recent measurements on long-lived neutral K particles.[16]

The various partial decay rates imply that the

[15] See, for example, G. Wentzel, Phys. Rev. **101**, 1215 (1956).

[16] Lande, Booth, Impeduglia, Lederman, and Chinowsky, Phys. Rev. **103**, 1901 (1956).

shortest of the three long lifetimes is that of K_-^s,

$$1/\tau_-^s = 2w_{\pi^0+\mu} + 2w_e + w_{3\pi} = (3\times10^{-8}\ \text{sec})^{-1},$$
$$1/\tau_-^a = 2w_{\pi^0+\mu} + 2w_e = (4\times10^{-8}\ \text{sec})^{-1},$$
$$1/\tau_+^a = 2w_{\pi^0+\mu} = (20\times10^{-8}\ \text{sec})^{-1}.$$

Of course, we have included here only processes having known counterparts for charged K particles, and other modes could be of importance; certainly the radiative decay into $\pi^+ + \pi^- + \gamma$ will contribute to $1/\tau_+^a$. Now we have conjectured that the disintegration $K_+^s \to \mu^+ + \mu^-$, proceeding through virtual μ pairs, is indirectly responsible for the short lifetime of this particle. Hence the decay $K_-^s \to \pi^0 + \mu^+ + \mu^-$ should exist although, since its charged counterpart $K_-^+ \to \pi^+ + \mu^+ + \mu^-$ has not been identified, it is to be presumed that the partial decay rate of this process ($w_-^s = w_{\pi^+ + 2\mu}$) is $<10^6$ sec^{-1}. Still more hypothetical is a coupling of neutral K particles with neutrino pairs. The disintegration of K_-^s into 2ν at a rate comparable to the $\mu\nu$ decays could significantly shorten the τ_-^s lifetime without producing any corresponding observable decay events. The only evidence relating to such neutrino pair couplings of K_+^s and K_-^s stems from the absence of any charged particle decays identified as $K^+ \to \pi^+ + 2\nu$.

Before discussing the various hyperon decay mechanisms, we must recognize that the g_K coupling could contain two distinct kinds of interactions. In the first type, K_+ is coupled with Λ_+, Σ_+, and K_- with Λ_-, Σ_- while the second one is obtained by replacing $\psi_{\Lambda+}$, for example, with $\gamma_5\psi_{\Lambda-}$ and $\psi_{\Lambda-}$ with $\gamma_5\psi_{\Lambda+}$. Thus the intrinsic parity degree of freedom is inert in one form of interaction and enters dynamically in the other. Since the necessity for the dynamical intrinsic parity appears with the $g_{\pi K}$ coupling, we shall argue that in the absence of π couplings the intrinsic parity, like hyperonic and nucleonic charge, has no explicit dynamical significance. Accordingly we choose the first type of g_K coupling, which can be characterized as producing K particles in s states relative to the Fermi-Dirac particles. If we now contrast $\Lambda_+ \leftrightarrow \bar{K}_+^0 + n$, $\bar{K}_+^- + p$ with $\Lambda_- \leftrightarrow \bar{K}_-^0 + n$, $\bar{K}_-^- + p$, we see that in Λ_+ the g_K coupling leads directly to the neutral K particle of positive parity involved in the decay mechanism, while with Λ_- the $g_{\pi K}$ coupling must also operate: $\bar{K}_-^0 \to \bar{K}_+^0 + \pi^0$, $\bar{K}_-^- \to \bar{K}_+^0 + \pi^-$. Hence the π mesons produced in the decay of Λ_+ arise from the $g_{\pi N}$ coupling and appear in p states, whereas with Λ_- decay the pions are generated by the $g_{\pi K}$ coupling and appear in s states. We naturally expect that it is the decay proceeding through the strong $g_{\pi N}$ coupling that possesses the shorter lifetime although the two lifetimes should not differ by more than an order of magnitude, which is consistent with the absence of Λ_- decays under the conditions employed in observing long-lived neutral K particles.[16] Some confirmation of this interpretation follows from the similar discussion of the Σ^+ decay mechanisms ($\Sigma_+^+ \leftrightarrow \bar{K}_+^0 + p$; $\Sigma_-^+ \leftrightarrow \bar{K}_-^0 + p$) where again the π mesons are produced by the $g_{\pi N}$ and $g_{\pi K}$ couplings, respectively. Thus the quite short lifetime observed for Σ^+ should be assigned to Σ_+^+. An elementary comparison of the decay rates for Σ_+^+ and Λ_+^0 yields

$$\tau(\Lambda)/\tau(\Sigma^+) = 2\left(\frac{p_\pi^3}{E_\pi^2}\right)_\Sigma \Big/ \left(\frac{p_\pi^3}{E_\pi^2}\right)_\Lambda \sim 7,$$

which is in reasonable accord with the presently accepted lifetimes.

Only in the hyperons Λ_+^0 and Σ_+^+ does the decay depend primarily upon the operation of the $g_{\pi N}$ coupling (of course, this and similar statements are made within the framework of an oversimplified approach to the strong interactions). For Λ_-, Σ_-^+, and Σ_-^-, the $g_{\pi K}$ coupling is the dominant mechanism and the various lifetimes are related by

$$\tau(\Lambda_-)/\tau(\Sigma_-^-) = 4/3 (p_\pi)_\Sigma/(p_\pi)_\Lambda \sim 2.5,$$
$$\tau(\Sigma_-^+)/\tau(\Sigma_-^-) = 2.$$

If the lifetime observed for Σ^- $[\tau(\Sigma^-) \sim \frac{1}{2}\tau(\Lambda)]$ is identified with that of Σ_-^-, we should conclude that $\tau(\Lambda_-) \sim \tau(\Lambda_+)$, in contrast with the apparent inference from associated production measurements that $\tau(\Lambda_-) > \tau(\Lambda_+)$. It would also be implied that Σ^+ possessed a second lifetime $\sim\tau(\Lambda)$. With the approximations used here, the decay of Σ_-^+ is entirely into $\pi^0 + p$, while Σ_+^+ decays into $\pi^+ + n$ and $\pi^0 + p$ with a branching ratio of 2:1. The relations among the various Σ decays illustrate and are limiting situations of general triangular inequalities connecting $(w_{\pi^+ + n})^{\frac{1}{2}}$, $(2w_{\pi^0 p})^{\frac{1}{2}}$ and $(w_{\pi^- - n})^{\frac{1}{2}}$.

The decay of Σ_+^- is more complicated than any yet considered since the K particle in $\Sigma_+^- \leftrightarrow \bar{K}_+^- + n$ must alter its charge without changing its intrinsic parity. This could be accomplished by the intervention of two π mesons: $\Sigma_+^- \to \bar{K}_+^- + n \to \pi^- + \bar{K}_-^0 + n \to \pi^- + \bar{K}_+^0 + n$, where the last stage indicates the effect of the interaction between the K meson and the nucleon that is propagated through the π-meson field. An alternative sequence is $\Sigma_+^- \to \bar{K}_+^- + n \to \bar{K}_-^- + n \to \pi^- + \bar{K}_+^0 + n$, and the two processes interfere. Indeed, in the related 2π decay of charged K particles the interference would be completely destructive if electromagnetic effects were not significant. One might also view these transformations as the charge exchange scattering by the K particle of a π^0 meson emitted from the neutron: $\Sigma_+^- \to \bar{K}_+^- + n \to \bar{K}_+^- + \pi^0 + n \to \bar{K}_+^0 + \pi^- + n$. The g_K coupling provides a means for K-particle charge exchange interaction with nucleons: $\bar{K}_+^- + p \to \Lambda_+^0$, $\Sigma_+^0 \to \bar{K}_+^0 + n$, which is the basis of another type of mechanism for Σ_+^- decay, $\Sigma_+^- \to \bar{K}_+^- + n \to \bar{K}_+^- + p + \pi^- \to \bar{K}_+^0 + n + \pi^-$. The branching ratio of 2:1 stated for $\pi^+ + n : \pi^0 + p$ involves the assumption that $\tau(\Sigma_+^-) \gg \tau(\Sigma_+^+)$. If, however, $\tau(\Sigma_+^-) = \tau(\Sigma^-) \sim 4\tau(\Sigma_+^+)$, the triangular inequalities supply only the information that the branching ratio is to be found between the limits of 9 and 0.6. The hyperon Ξ^- decays alternatively into Λ_+^0, accompanied by a π^- meson in a p state, or into Λ_-^0 and an s-state π^- meson.

The latter process is another example of π production through the $g_{\pi K}$ coupling, $\Xi^-\to\bar{K}_-^-+\Lambda_-^0\to\bar{K}_+^0+\pi^-+\Lambda_-^0$. With $\Xi^-\leftrightarrow\bar{K}_+^0+\Sigma_+^-$; $\bar{K}_+^-+\Lambda_+^0$, Σ_+^0, however, a nucleon must be produced to supply the π meson. The g_K coupling leads to $\bar{K}_+^0+\bar{K}_+^-+n$, and, after the emission of π^- by the neutron, $\bar{K}_+^-$ and p combine to form Λ_+^0. In view of the possible existence of two distinct Λ lifetimes, a study of the decay properties of the Λ particles observed in Ξ^- decay might be of value.

We want to comment here on the neutral K particles produced in association with Ξ^-, as in the reaction $n+n\to K^0+K^0+\Xi^-+p$. For a collision that is completely specified, apart from the intrinsic parity of the K particles, the final state would be of the form

$$\beta_1|K_1^0K_1^0\rangle+\beta_2|K_2^0K_2^0\rangle =\tfrac{1}{2}(\beta_1+\beta_2)(|K_+^0K_+^0\rangle+|K_-^0K_-^0\rangle) +2^{-\frac{1}{2}}(\beta_1-\beta_2)|K_+^0K_-^0\rangle,$$

where

$$\tfrac{1}{2}|\beta_1+\beta_2|^2+\tfrac{1}{2}|\beta_1-\beta_2|^2=1.$$

This state can also be written as

$$\tfrac{1}{4}(\beta_1+\beta_2)|K_+^sK_+^s\rangle+2^{-\frac{3}{2}}(\beta_1+\beta_2)|K_+^sK_+^a\rangle +\tfrac{1}{2}(\beta_1-\beta_2)|K_+^sK_-^0\rangle+\tfrac{1}{4}(\beta_1+\beta_2)|K_+^aK_+^a\rangle +\tfrac{1}{2}(\beta_1+\beta_2)|K_-^0K_-^0\rangle+\tfrac{1}{2}(\beta_1-\beta_2)|K_+^aK_-^0\rangle,$$

in which the various two-particle states have been grouped in accordance with the number of K_+^s particles that are contained. On recalling the visibility factor of $\frac{2}{3}$ for the fast θ^0 decay mode, we see that the probabilities for the Ξ^- particle to be accompanied by two θ^0 decays, or by one θ^0 decay, are given by

$$p_{2\theta^0}=1/18\times\tfrac{1}{2}|\beta_1+\beta_2|^2$$
$$p_{1\theta^0}=4/18\times\tfrac{1}{2}|\beta_1+\beta_2|^2+\tfrac{1}{3}\times\tfrac{1}{2}|\beta_1-\beta_2|^2.$$

Hence, one should, at most, observe $\frac{1}{4}$ as many $2\theta^0+\Xi^-$ decays as $\theta^0+\Xi^-$ decays. Thus far one event of each type has been reported.[1]

Finally, we must emphasize that all these discussions of K particle and hyperon decays refer to isolated particles, whereas the experimental observation of a decay process usually requires that it occur in dense matter. Now the particles with dynamical intrinsic parity are sensitive to disturbance by external π fields, which produce an interconversion of the two parity types. If, in its passage through matter, the particle penetrates often enough into regions occupied by π fields that parity conversions are produced at a rate considerably in excess of $\frac{1}{2}|w_+-w_-|$, the particle decay will not exhibit the two lifetimes τ_+ and τ_- but rather the single lifetime τ, given by

$$\frac{1}{\tau}=\frac{1}{2}\left(\frac{1}{\tau_+}+\frac{1}{\tau_-}\right).$$

In effect, the particle will then maintain its parity symmetry, despite the tendency of the decay mechanisms to distinguish the two intrinsic parities. This comment will acquire major significance if an anticipated multiple-lifetime decay is definitely not observed, under experimental circumstances for which such parity conversions are conceivable.