

The Interpretation of the New Particles as Displaced Charge Multiplets.

M. GELL-MANN (*)

Institute for Advanced Study, Princeton, N. J.

1. – Introduction.

The purpose of this communication is to present a coherent summary of the author's theoretical proposals [1] concerning the new unstable particles.

Section 2 is devoted to some background material on elementary particles; the object there is to introduce the point of view adopted in the work that follows. In Section 3 the fundamental ideas about displaced multiplets are given, and in the succeeding section these are applied to the interpretation of known particles. A scheme is thus set up, which is used in Section 5 to predict certain results of experiments involving the new particles.

2. – General remarks on elementary particles.

2'1. *Particle and antiparticle.* – We begin by accepting the postulate that physical laws are invariant under the operation of charge conjugation, which carries every microscopic system into a corresponding charge-conjugate system, with equal and opposite charge and magnetic and electric moments. The charge-conjugate of a particle will be referred to as its «antiparticle». The invariance principle then requires particle and antiparticle to have the same mass and lifetime, charge-conjugate decay products, and so forth. If the electric charge is zero, particle and antiparticle may be identical; such is the case with the photon and neutral pion, but not with the neutron, which has a magnetic moment.

(*) Now at Department of Physics, California Institute of Technology, Pasadena, California.

2'2. *Groups of particles.* — The particles of atomic physics seem to fall into four groups

(A) The heavy particles or « baryons », including the neutron and proton and all known hyperons, and their anti-particles, the « antibaryons ».

All these are fermions obeying an overall conservation law which is, so far as is known, exact, viz: the quantity n , the number of baryons minus the number of antibaryons, is conserved in all physical processes.

(B) The light fermions or « leptons », including the muon, the electron, and the neutrino. If K-particles exist that are fermions, they presumably belong in this category.

(C) The « mesons ». The term « meson » will be used here to denote pions and heavier bosons exclusively. The muon, for example, is then *not* a « meson » but a « lepton ».

(D) The photon.

2'3. *Types of interaction.* — The interactions amongst elementary particles seem also to have a natural classification. There are three types:

(i) The strong interactions, confined to baryons, antibaryons, and mesons. These are responsible for nuclear forces and the production of mesons and hyperons in high energy nuclear collisions.

(ii) The electromagnetic interaction, through which the photon is linked to all charged particles, real or virtual.

(iii) The weak interactions, responsible for β -decay, the slow decays of hyperons and K-particles, the absorption of negative muons in matter, and the decay of the muon.

We will adopt the point of view that nature is most easily described by a sequence of approximations. In the first of these, interactions of types (ii) and (iii) are « turned off ». Leptons and the photon are then totally non-interacting. Baryons, antibaryons, and mesons undergo reactions and transformations obeying laws peculiar to the strong interactions, while decays involving leptons and photons cannot, of course, occur. In the second approximation, the charges of particles are turned on, so that types (i) and (ii) are effective, but still not (iii). The processes involving baryons, antibaryons, and mesons are now modified by electromagnetic effects; and decays involving photons are permitted. The leptons remain uncoupled except for electromagnetism. In the final approximation, which is as exact a description of matter as we can conceive of at present (apart from gravitation), the weak interactions are turned on.

2'4. *The ordinary particles; charge independence.* — We shall refer to the nucleon (\mathcal{N}), the antinucleon ($\overline{\mathcal{N}}$), and the pion (π) as « ordinary particles » to distinguish them from the « strange particles », K-particles and hyperons. Let us review here some conventional theoretical ideas about these ordinary particles, ignoring the strange ones for the time being.

The first approximation, in which only the strong interactions appear, is characterized by the stability of \mathcal{N} , $\overline{\mathcal{N}}$, and π (since electromagnetic and leptonic decays cannot occur) and also by the principle of charge independence or conservation of isotopic spin, which we go on to describe.

Each real or virtual particle carries an isotopic spin vector \mathbf{I} , and the total \mathbf{I} is exactly conserved. Each particle belongs to a rigorously degenerate multiplet with an isotopic spin quantum number I and multiplicity $2I+1$. The components of each multiplet are distinguished in charge by the z -component of the isotopic spin vector and are spaced one charge unit apart, with increasing charge corresponding to increasing I_z . The center of charge, or average charge, of the multiplet varies. For the nucleon doublet, the center is at $e/2$, for the antinucleon doublet at $-e/2$, for the pion triplet at 0. We may summarize the distribution of charges by the relation

$$(2.1) \quad Q/e = I_z + \frac{n}{2},$$

where Q is the charge and n is defined as in (A), so that here it means the number of nucleons minus the number of antinucleons. Since Q , I_z and n are all additive, equation (2.1) holds for any system of ordinary particles, for example an atomic nucleus. The center of charge of a multiplet is always $(n/2)e$.

In the second approximation, the electromagnetic interaction, which is of course charge-dependent, is turned on. The conservation of I^2 is then violated. Moreover, the isotopic spin degeneracy is lifted so that a mass difference appears between the charged and neutral pion and between the neutron and proton [2]. (The assumption that these mass differences are electromagnetic in origin is somewhat controversial and not essential to our arguments, but we shall adopt it anyway as fitting in well with the general point of view). The electromagnetic interaction also induces the decay of the neutral pion into two γ -rays.

Finally, with the turning on of the weak interactions, the β -decay of the neutron becomes possible and also the decay of the charged pion into muon and neutrino or into electron and neutrino. (The latter process has never been detected with certainty and is apparently very rare.)

2'5. *Rapid, electromagnetic, and slow processes.* — We may use the ordinary particles to illustrate some important distinctions of which we will make

further use. A process that can occur in the first approximation will be called « rapid ». Similarly, one that can occur in the second but not in the first approximation will be known as an « electromagnetic » process. A process that can take place in the third approximation only will be called « slow » (*).

Let us now examine some decay processes among the ordinary particles. The nucleon « isobar » that supplies the resonance in pion-nucleon scattering in the state with $I = \frac{3}{2}$ and $J = \frac{3}{2}$ may be thought of as a particle that disintegrates into nucleon and pion with a lifetime of the order of 10^{-23} seconds. This decay is fully allowed by conservation of I and is induced by the strong interactions; it is a typical rapid decay. The order of magnitude of the lifetime is given by the nuclear dimension divided by the velocity of light, since there are no important effects of barrier penetration or of unusually limited available volume in phase space.

The decay of the neutral pion is impossible in the first approximation since there is no lighter meson for it to turn into. With the turning on of charges, however, its decay into γ -rays becomes possible; that process is thus « electromagnetic ». The lifetime should be of the order of $(e^2/\hbar c)^2$ times 10^{-23} s but is actually much longer ($\sim 10^{-15}$ s) for reasons that are not entirely clear. (A simple perturbation theoretic calculation in meson theory gives $\sim 10^{-17}$ s).

The charged pion cannot decay even in the second approximation since it must emit a lighter charged particle. The weak interactions, of course, induce a « slow » leptonic decay. The lifetime is now very long ($\sim 10^{-8}$ s) because the coupling constant of the weak interactions enters.

In high energy collisions, as opposed to decays, the rapid processes are usually the only ones observed (for example, pion production in nucleon-nucleon collisions.) Some electromagnetic processes are detectable in high energy collisions (particularly when a photon is the bombarding particle, as in the photopion effect.) Slow processes, however, are generally out of the question as regards observation on account of their tiny cross-sections. (For example, we should not expect to observe direct electron and neutrino production in nuclear collisions.) It is fair to say, then, that interactions of type (iii) can be ignored in collisions.

3. – The principal features of the model.

3'1. *Generalized charge independence; displaced multiplets and strangeness.*

– The first assumption on which our interpretation of hyperon and K-particle

(*) Among the slow processes are some, such as the radiative decay $\pi \rightarrow \mu + \nu + \gamma$, which require the intervention of both weak and electromagnetic effects. These might be called « slow electromagnetic » processes.

phenomena is based is a generalized principle of charge independence. We postulate that isotopic spin is exactly conserved in the first approximation not only for ordinary particles but for the entire complex of baryons, mesons, and antibaryons. In other words, all strong interactions are supposed to be charge independent, and all baryons, mesons, and antibaryons are supposed to be grouped in charge multiplets.

We abandon, however, the restriction given by equation (2.1) on the location of the center of charge of each multiplet. While retaining the principle that Q/e be given by $(I_z + \text{constant})$ for each multiplet, we do not require that the constant be $n/2$, but allow it to be arbitrary. We shall write this arbitrary constant, which specifies the center of charge of the multiplet, as $n/2 + S/2$, where S is integral. We have, then, in place of equation (2.1) the relation

$$(3.1) \quad Q/e = I_z + \frac{n}{2} + \frac{S}{2},$$

where S may vary from multiplet to multiplet.

The ordinary particles are characterized, then, by having $S = 0$. A particle with $S \neq 0$ is a member of a «displaced» multiplet, with center of charge at a position different from that with which we are familiar among the ordinary particles. For example, we might find a baryon triplet consisting of a positive, a neutral, and a negative member. The center of charge is at zero rather than $\frac{1}{2}e$ as it is for the nucleon doublet. The corresponding value of S is -1 .

We propose to identify all known hyperons and K-particles as members of displaced multiplets and to account for some of their properties in that way. Since we have $S = 0$ for ordinary particles and $S \neq 0$ for «strange» ones we refer to S as «strangeness».

It should be remarked that in (3.1) the quantities Q , I_z and n all change sign under charge conjugation, so that S must also.

3.2. Conservation of strangeness; laws of stability and associated production. — In the first approximation, our principle of generalized charge independence implies the usual selection rules and intensity formulae characteristic of isotopic spin conservation, as well as the rigorous degeneracy of charge multiplets. Most of these rules become approximate when the electromagnetic interactions are turned on. Let us concentrate our attention on one that, as we shall see later, *remains rigorous in the second approximation*. That one is the conservation of strangeness (*), which follows from the conservation of I_z by the strong interactions, the exact conservation of Q and n , and equation (3.1).

(*) It should be emphasized that the conservation of strangeness is nothing but the conservation of I_z restated in a more convenient form.

The conservation of strangeness gives rise to two important qualitative effects:

1) The law of stability: A strange particle cannot decay rapidly into ordinary ones.

2) The law of associated production (*). In a collision of ordinary particles, there can be no rapid formation of a single strange particle; there must be at least two of them and the total strangeness must be zero.

These laws, while merely special cases of the conservation of S , are quite striking. It is the law of stability that gives us a clue to understanding the long lifetimes of the new particles. That the metastability of the particles would be coupled with associated production has been predicted by a number of physicists [3].

3'3. *Minimal electromagnetic interaction.* — We still need, of course, the result that the conservation of S remains valid in the second approximation, so that the decay of strange particles is a slow process, induced only by the weak interactions. This result cannot be proved without an assumption about the nature of the electromagnetic interaction.

We shall postulate a principle that is given wide, though usually tacit acceptance, that of minimal electromagnetic interaction. Before attempting to state the principle, let us illustrate its application to two familiar examples.

It is possible to describe the « anomalous » magnetic moments of the neutron and proton by introducing a specific interaction of the Pauli type between the spins of these particles and the electromagnetic field. In the language of field theory, one adds to the Lagrangian density a term of the form $\gamma_p \bar{\psi}_p \sigma_{\mu\nu} \psi_p F_{\mu\nu} + \gamma_n \bar{\psi}_n \sigma_{\mu\nu} \psi_n F_{\mu\nu}$, where the γ 's are constants, $F_{\mu\nu}$ is the electromagnetic field strength tensor, and the ψ 's are field operators describing proton and neutron. However, this description is not usually adopted, except in frankly phenomenological discussions. It is supposed instead, following WICK [4], that the anomalous moments appear as a result of the virtual dissociation of the nucleon, say into nucleon plus mesons. The interaction of the electromagnetic field with the charges and currents in the dissociated system appears in some respects like a Pauli interaction with the nucleon spin. The important point is that, having introduced the Yukawa hypothesis of a meson cloud around the nucleon, one does not need any *special* electromagnetic interaction. The usual coupling of the electromagnetic field to the nucleon and meson fields is supposed to be sufficient.

(*) This very apt name seems to have originated with Dr. M. G. K. MENON.

The second example is the decay of the neutral pion into two γ -rays. We may account for this process too by means of a special interaction. If φ is the field operator describing the π^0 , we may write the interaction Lagrangian density as $K\varphi F_{\mu\nu}^* F_{\mu\nu}$. Here K is a constant and the star indicates the dual of the field strength tensor. Here again such a description is not customary except as a phenomenological device. Instead it is believed that the decay is due to the virtual dissociation of the pion, say into proton and antiproton, and that the electromagnetic field enters only through its customary interaction with the charged virtual particles involved.

We may state the principle involved roughly as follows: The photon possesses no interactions except the usual one with the charges and currents of real and virtual particles. Within the framework of present-day local field theories, we may give a more precise statement: Given the Lagrangian with all electric charges turned off, but all other effects included, the coupling of the electromagnetic field is introduced by making the substitution

$$(3.2) \quad \frac{\partial}{\partial x_\mu} \rightarrow \frac{\partial}{\partial x_\mu} - iQ A_\mu(x),$$

whenever the gradient occurs acting on a field operator (Q being the charge of the particle annihilated by the field operator in question); there is no other electromagnetic interaction.

It is now easy to show that the conservation of S remains valid in the second approximation. Since for each multiplet we have $Q = I_z + \text{const}$ and since the electromagnetic coupling is through the charge alone, the coupling Hamiltonian transforms in isotopic spin space like a function of I_z and thus commutes with the total I_z . It follows, that I_z is conserved even after the charges are «turned on»; and so, according to (3.1), S is conserved, too.

It is instructive to see how, if the electromagnetic coupling is *not* minimal, conservation of strangeness may be lost in the second approximation. Let us imagine a charged meson field with strangeness $+1$ for the positive particle, B^+ , and, correspondingly, -1 for the negative one, B^- . Let us further suppose for simplicity that the field is scalar. Now since we are dealing with a strange particle the virtual dissociation $p \rightarrow n + B^+$ is forbidden in the first approximation. We could, however, by introducing a special electromagnetic interaction, allow the dissociation to occur with the emission of a photon, $p \rightarrow n + B^+ + \gamma$. We might take for the interaction Lagrangian density an expression of the form

$$(3.3) \quad K \bar{\psi}_p \sigma_{\mu\nu} \psi_n \chi F_{\mu\nu} + \text{c.c.}$$

The forbidden dissociation could now take place in two steps: $p \rightarrow n + B^+ + \gamma$ and then $B^+ + \gamma \rightarrow B^+$. Instead of being a slow process, $p \rightarrow n + B^+$ would

be an electromagnetic one. It is in order to avoid situations like this that we require the electromagnetic interaction to be minimal.

3'4. *The violation of S -conservation by the weak interactions.* — The weak interactions are responsible for three sorts of processes: those involving leptons alone, like the decay of the muon; those involving only strongly interacting particles (*), like the decay of the Λ^0 into proton and negative pion; and those connecting leptons with strongly interacting particles (*), like the decay of the charged pion or of the neutron.

We need not concern ourselves with the first sort, since our purpose is to discuss hyperons and K-particles. The second sort of process is of considerable interest to us, however. We recall that the proposal is advocated here that the long lifetimes of such particles as the Λ^0 are to be attributed to their having $S \neq 0$, so that the decay into ordinary particles is forbidden in the first and second approximations. The decay does, however, occur in fact, though slowly. We must suppose, therefore, that in such decays as $\Lambda^0 \rightarrow p + \pi^-$ the conservation of strangeness is violated by the weak interactions. The weak interactions involving strongly interacting particles are thus charge-dependent; they do not conserve isotopic spin. Indeed, they do not conserve even the z -component of the total isotopic spin, as the electromagnetic interactions do.

The last sort of process, like the second, provides slow decay modes for particles that would be stable in the absence of the weak interactions. In this case, however, the decay products include leptons, for which isotopic spin and strangeness are probably not well-defined concepts. An example amongst the new particles is provided by the $K_{\mu 2}^+$ events, in which a strange meson apparently decays slowly into a muon and a neutrino.

4. — The classification of known particles.

We must now investigate whether the properties of known hyperons and K-particles are consistent with the principles of Section 3. Let us concentrate our attention first on hyperons.

4'1. *The Λ^0 singlet.* — If the Λ^0 -particle is to be considered a member of a charge multiplet, that multiplet must surely be a singlet, since no charged counterpart of the Λ^0 has ever been found with similar mass. (The lightest charged hyperons known are heavier by more than 150 electron masses). A

(*) I.e., baryons, antibaryon, and mesons.

neutral singlet is perfectly satisfactory, of course, and corresponds to a strangeness of minus one. The metastability of the Λ^0 is then explained; since it is the lightest hyperon, and since it is lighter than a nucleon plus any K-particle, it cannot decay without violating the conservation of strangeness. The slow decay into ordinary particles (nucleon plus pion) is induced by the weak interactions.

4.2. *The Σ triplet.* — The lightest known hyperons after the Λ^0 are the charged particles called Σ^+ and Σ^- , which decay slowly into nucleon and pion like the Λ^0 but with a much higher Q -value (~ 115 MeV). Since no doubly-charged hyperons have been observed, we are forced to class the Σ as a charge triplet, including a hypothetical Σ^0 . The strangeness of the Σ is then minus one like that of the Λ . The metastability of the Σ^+ and Σ^- can be understood since there is not enough energy for $\mathcal{N} + K$ nor for $\Lambda + \pi$. For the Σ^0 , the situation is different. While $\mathcal{N} + K$ and $\Lambda + \pi$ are still energetically impossible modes of decay just as for the charged Σ , there is the possibility of an electromagnetic decay $\Sigma^0 \rightarrow \gamma + \Lambda^0$, and Σ and Λ have equal strangeness. Thus we do not expect Σ^0 to be metastable but rather to have a lifetime $\sim 10^{-20}$ s, and we can understand why it has not been discovered in the same way as the Λ^0 . The experimental detection of the Σ^0 will be discussed in the next section.

4.3. *Cascade hyperons.* — The existence of one other hyperon is well established, and that is the negative cascade particle Ξ^- , which yields $\Lambda^0 + \pi^-$ in a slow decay. No positive or doubly charged counterpart has been found, and so we have two choices for the assignment of the Ξ : it can be a singlet with strangeness minus three, or it can form a doublet with strangeness minus two along with a hypothetical Ξ^0 . With either assignment we can understand the metastability of the Ξ , since there is not enough energy for the emission of a K-particle, and the decay, into \mathcal{N} , Λ or Σ with the emission of pions or γ -rays is forbidden by conservation of strangeness.

4.4. *The rule $\Delta S = \pm 1$; the Ξ doublet.* — We may choose between the two possible assignments if we add a new principle to those of Section 3. We begin by remarking that while the process $\Xi^- \rightarrow \pi^- + \Lambda^0$ has been observed about a dozen times, there is no evidence for $\Xi^- \rightarrow \pi^- + n$. Let us suppose that the latter does not in fact occur. Then apparently there is a rule governing the change in strangeness when the weak interactions act to induce the decay of a strongly interacting particle into other strongly interacting particles. Now we know that in the decay of the Λ into nucleon and pion, the strangeness changes by one unit. The only *simple* rule there could be is

thus (*)

$$(4.1) \quad \Delta S = \pm 1 \quad \text{or} \quad \Delta I_z = \pm \frac{1}{2}.$$

We are then forced to assign $S = -2$ to the cascade particle. The slow decay into a Λ is consistent with (4.1) and the unobserved slow decay into a nucleon is not. The Ξ^0 must exist, according to this assignment, but we can easily see why it has not yet been observed; the only slow decay consistent with (4.1) is (+)

$$(4.2) \quad \Xi^0 \rightarrow \Lambda^0 + \pi^0.$$

4.5. K-particle doublets. — We may now turn to the heavy mesons. In view of our rule (4.1), any K-particle that decays into pions with a typical strange particle lifetime must be assigned $S = \pm 1$. Since no multiply charged mesons are known, there is only a single possibility for the isotopic spin assignments of such mesons, viz: a doublet with $S = \pm 1$, consisting of a positive and a neutral member (K^+ and K^0), and the charge-conjugate doublet with $S = -1$, consisting of a negative and a neutral member (K^- and \bar{K}^0). The K^0 and the \bar{K}^0 have opposite strangeness and thus cannot be the same particle; the consequences of this situation have been explored in another publication [5] and will not be treated fully here. Suffice it to say that present direct experimental evidence cannot decide for or against the hypothesis that strange neutral mesons possess distinct anti-particles.

4.6. The θ doublets. — The θ^0 is presumably a member of a pair of doublets such as we have described. The existence of charged counterparts θ^+ and θ^- is now fairly well established. Of course without experimental proof that the θ^0 and $\bar{\theta}^0$ are distinct, one might try to treat the θ as a charge triplet, but that would clearly be totally inconsistent with the point of view developed here.

The metastability of the θ is evident in our picture, provided there is no lighter meson of the same strangeness. We must look into this point carefully, and examine all known decay modes of K-particles to see how many distinct varieties of heavy mesons there may be.

4.7. The τ -meson. — Besides the θ^\pm , at least one other charged meson of roughly the same mass is known: the τ -meson, which decays into three pions

(*) The rule $\Delta S = \pm 1$ applies when the weak interactions act once in the sense of perturbation theory. A decay in which they act twice could, of course, have $\Delta S = \pm 2$ but the lifetime for such a process would be very long, say a second or even a day.

(+) There are also the slow electromagnetic decays $\Xi^0 \rightarrow \Sigma^0 + \gamma$ and $\Xi^0 \rightarrow \Sigma^0 + \gamma$.

rather than two. The work of DALITZ on the τ -meson decay spectrum indicates that the θ and τ have different parity and/or spin and thus cannot be merely two decay modes of the same particle.

Thus we expect a second pair of doublets, τ^+ , $\tau^{(0)}$, $\overline{\tau^{(0)}}$, and τ^- , with strangeness ± 1 like the θ . The neutral partners, if they are as long-lived as the charged ones, could easily have escaped definite identification.

The reason for the similarity in mass of the τ and θ is of course completely unknown, but there is a further puzzle. The masses are presumably not exactly equal, and there is the possibility of electromagnetic decay of the heavier into the lighter, fully allowed by conservation of strangeness. Since both the τ and θ are metastable, something must inhibit such electromagnetic decay so that it takes at least 10^{-9} s to occur. It may be that the mass difference is very small, considerably smaller than 1 MeV, say; or it may be that the τ and θ are both spinless (the τ pseudoscalar and the θ scalar), in which case we are dealing with a $0 \rightarrow 0$ transition.

4'8. *Leptonic decays.* — Three leptonic decays of K-particles are known:

$$(4.3) \quad K_{\mu} \rightarrow \mu + \nu$$

$$(4.4) \quad \kappa \rightarrow \mu + 2 \text{ neutrals, presumably } \kappa \rightarrow \mu + \nu + \pi^0$$

$$(4.5) \quad K_{\beta} \rightarrow e + 2 \text{ neutrals, presumably } K_{\beta} \rightarrow e + \nu + \pi^0.$$

All of these particles are of roughly the same mass as the τ and θ and may represent simply alternative decay modes of those mesons. If they are really distinct particles, then further theoretical problems of degeneracy and electromagnetic stability are presented. It is clearly most important to have an experimental determination, for example by accurate lifetime or mass measurements, of how many different mesons there are with masses close to $1000 m_e$. In the meantime, the simplest assumption is surely that there are only the θ and the τ and that leptonic decays compete with decays into pions.

Leptonic decays of hyperons, for example

$$(4.6) \quad \Lambda^0 \rightarrow p + e^- + \nu,$$

should presumably occur also. They may compete less favorably with pionic decays than the corresponding processes for K-particles and so have escaped observation.

4'9. *Summary.* — We have identified, among the hyperons, a singlet with $S = -1$ (Λ^0), a triplet with $S = -1$ (Σ^+ , Σ^0 , Σ^-), and a doublet with

$S = -2$ (Ξ^0 , Ξ^-). Among the K-particles, we have the θ and $\bar{\theta}$ doublets (with $S = \pm 1$) and the τ and $\bar{\tau}$ doublets (with $S = \pm 1$).

We have noted the phenomenological law that $\Delta S = \pm 1$ ($\Delta I_z = \pm \frac{1}{2}$) for slow decays within the complex of baryons, mesons, and antibaryons. Leptonic decays, also induced by the weak interactions (and for which ΔS is not a well-defined quantity if we include the leptons), may compete with these processes.

5. - Predictions of phenomena involving the new particles.

5.1. *Conservations of Strangeness in π - \mathcal{N} and \mathcal{N} - \mathcal{N} Collisions.* - We have already remarked that in π - \mathcal{N} and \mathcal{N} - \mathcal{N} collisions, since the total initial strangeness is zero, strange particles must be produced at least two at a time, and the sum of their S -values must be zero. Now that we have assigned values of S to all known strongly interacting particles, we can list which reactions are allowed (*A*) and which forbidden (*F*) by conservation of strangeness (*). It should be remarked that any number of π 's may be added to the reaction products in each case without changing the designation (*A*) or (*F*).

In the list that follows we shall ignore all reactions in which a single strange particle is produced, since those are obviously forbidden. We shall use the symbol B to denote θ^0 , θ^+ , τ^0 , or τ^+ , and \bar{B} to denote $\bar{\theta}^0$, θ^- , $\bar{\tau}^0$ or τ^- .

$$(5.1) \quad \pi + \mathcal{N} \rightarrow \Lambda + B \quad \text{or} \quad \Sigma + B \quad (A)$$

$$(5.2) \quad \pi + \mathcal{N} \rightarrow \Lambda + \bar{B} \quad \text{or} \quad \Sigma + \bar{B} \quad (F)$$

$$(5.3) \quad \pi + \mathcal{N} \rightarrow \mathcal{N} + B + \bar{B} \quad (A)$$

$$(5.4) \quad \pi + \mathcal{N} \rightarrow \Lambda + B + \bar{B} \quad \text{or} \quad \Sigma + B + \bar{B} \quad (F)$$

$$(5.5) \quad \pi + \mathcal{N} \rightarrow \Xi + B \quad (F)$$

(*) If the designation (*A*) is taken to mean that a reaction so labeled will naturally occur with an appreciable cross-section, then use is being made of what we may call the «Principle of Compulsory Strong Interactions». Among baryons, antibaryons, and mesons, any process which is not forbidden by a conservation law actually does take place with appreciable probability. We have made liberal and tacit use of this assumption, which is related to the state of affairs that is said to prevail in a perfect totalitarian state. Anything that is not compulsory is forbidden.

Use of this principle is somewhat dangerous, since it may be that while the laws proposed in this communication are correct, there are others, yet to be discussed, which forbid some of the processes that we suppose to be allowed.

$$(5.6) \quad \pi + \mathcal{N} \rightarrow \Xi + \bar{B} \quad (F)$$

$$(5.7) \quad \pi + \mathcal{N} \rightarrow \Xi + B + \bar{B} \quad (F)$$

$$(5.8) \quad \pi + \mathcal{N} \rightarrow \Xi + \bar{B} + \bar{B} \quad (F)$$

$$(5.9) \quad \pi + \mathcal{N} \rightarrow \Xi + B + B \quad (A)$$

$$(5.10) \quad \mathcal{N} + \mathcal{N} \rightarrow \Lambda + \Lambda \quad \text{or} \quad \Lambda + \Sigma \quad \text{or} \quad \Sigma + \Sigma \quad (F)$$

$$(5.11) \quad \mathcal{N} + \mathcal{N} \rightarrow \Lambda + \mathcal{N} + B \quad \text{or} \quad \Sigma + \mathcal{N} + B \quad (A)$$

$$(5.12) \quad \mathcal{N} + \mathcal{N} \rightarrow \Lambda + \mathcal{N} + \bar{B} \quad \text{or} \quad \Sigma + \mathcal{N} + \bar{B} \quad (F)$$

The reader may easily extend this list to cover all reactions that can be written down. Let us notice that among those we have included are some striking predictions. From (5.1) and (5.2) we see that the reaction $\pi^- + p \rightarrow \Sigma^- + \theta^+$ is allowed, while the reaction $\pi^- + p \rightarrow \Sigma^+ + \theta^-$ is forbidden. In fact, the threshold for θ^- production is much higher than that for θ^+ production. While a θ^+ may be made with the conversion of a nucleon into a hyperon, a B^- can only be made along with a B^0 or a B^+ (*).

From (5.10)-(5.12) we see that the threshold for strange particle production in \mathcal{N} - \mathcal{N} collisions is much higher than one would have guessed if one knew only that two strange particles must appear. The reactions with the lowest thresholds ($\mathcal{N} + \mathcal{N} \rightarrow$ two hyperons) are all forbidden, and strange particles can be produced only when there is enough energy for the process $\mathcal{N} + \mathcal{N} \rightarrow \Lambda + \mathcal{N} + B$.

We may remark, too, that in order to produce a Ξ two B-mesons must be made at the same time (see (5.5)-(5.9)). Thus the threshold for Ξ production is very high indeed.

From (5.1) we observe that besides the reaction

$$(5.13) \quad \pi^- + p \rightarrow \Lambda^0 + \theta^0$$

there is also the possibility of

$$(5.14) \quad \pi^- + p \rightarrow \Sigma^0 + \theta^0 \rightarrow \gamma + \Lambda^0 + \theta^0$$

as well as

$$(5.15) \quad \pi^- + p \rightarrow \Lambda^0 + \pi^0 + \theta^0.$$

(*) Unless there exists a hitherto undiscovered hyperon of positive strangeness.

Now process (5.14) affords a possibility of detecting the Σ^0 experimentally [5]. In a magnetic cloud chamber it resembles (5.13) but with an apparent lack of conservation of energy and momentum. Of course careful observation is necessary to establish the effect and to distinguish it from (5.15), which looks similar.

5.2. *The absorption of negative strange particles in nuclear matter.* — We are able to predict in general terms what will happen when a negative strange particle comes to rest in matter, and thus in the vicinity of a nucleus. In all such cases that are known there is a rapid exothermic process that can occur. Slow processes, such as spontaneous decay, will not be able to compete. The situation is similar to that of a stopped negative pion, which can undergo rapid absorption by a nucleus and thus does not have the opportunity to decay.

For the Σ^- particle, there is the allowed reaction

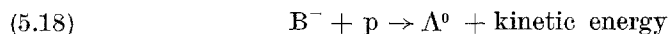


which releases about 80 MeV of kinetic energy. For the Ξ^- , there is the process



with a Q -value of about 30 MeV. These energy releases are much less than what one would expect in each case if the hyperon were to decay and the emitted pion were to be absorbed by the nucleus, a course of events that we predict will not take place. (The energy released in such a situation would be about 250 MeV for the Σ and 200 MeV for the Ξ .) It has been pointed out, however, by M. G. K. MENON [7] that in reactions (5.16) and (5.17) (particularly (5.17)) an emitted Λ^0 may become trapped in the nucleus (as in the so-called «hyperfragments») and much later undergo a decay, releasing 176 MeV in the form of a pion and kinetic energy. If this pion is in turn absorbed by the nucleus, the full 176 MeV may appear as kinetic energy besides the Q -value of (5.16) or (5.17).

A θ^- or a τ^- particle (for which we shall use the symbol B^-) may be absorbed rapidly through reactions such as



$$(5.22) \quad B^- + p \rightarrow \Sigma^0 + \pi^0 \rightarrow \gamma + \Lambda^0 + \pi^0$$

$$(5.23) \quad B^- + p \rightarrow \Lambda^0 + \pi^+ + \pi^-$$

$$(5.24) \quad B^- + n \rightarrow \Lambda^0 + \pi^-$$

etc.

It is to be expected that processes such as (5.16), (5.17), and (5.19) in which the products are neutral may often lead to zero prong stars in photographic emulsions.

5'3. *Binding of strange particles to nuclei; hyperfragments.* — We have seen that the known negative strange particles cannot form metastable combinations with nuclei, but are instead rapidly absorbed. It is known, though, that the Λ^0 does form such combinations, the « hyperfragments », in which the hyperon is bound by nuclear forces to nucleons. The metastability of the fragments containing Λ^0 's is perfectly comprehensible in our scheme. The bound Λ^0 cannot undergo a rapido exothermic reaction in nuclear matter since there is no lighter system of the same strangeness. It thus survives until it decays spontaneously. The pion released in the decay may emerge or may be absorbed by the nucleus.

We may now inquire whether any other particles may form « fragments » besides the Λ^0 . It is easy to show, by exhibiting reactions such as (5.18)-(5.24), that no other known hyperon and no \bar{B} particle can be metastable in the presence of nuclear matter containing both neutrons and protons (*). The B particles (θ^0 , θ^+ , τ^0 , τ^+) may, however, form metastable bound systems with nuclear matter *provided their nuclear forces are attractive and strong enough to bind*. The strangeness of a B-particle is $+1$ and no way is known for this strangeness to be conserved in an exothermic reaction with nucleons. Of course it may be that a hyperon Z of strangeness $+1$ will be discovered; in order to be metastable, its mass must be less than the mass of a nucleon plus the mass of a B meson. If Z exists, then a B meson is no longer metastable in nuclear matter; however, Z is.

There are special cases in which heavy hyperons may form fragments. Dr. W. HOLLADAY has pointed out [8] that in our scheme a Σ^- or Ξ^- may form a metastable fragment with neutrons alone. (Reactions (5.16)-(5.17) cannot then take place.) The same is true of a Ξ^0 or Σ^+ and protons alone.

5'4. *Interactions of strange particles in flight.* — We have shown that very slow strange particles interacting with nuclei should exhibit two types of

(*) The reader will notice the appeal to the « Principle of compulsory strong interactions ».

behavior: Λ^0 's and B mesons should retain their identity until they decay spontaneously; heavier hyperons and \bar{B} mesons should be readily absorbed by the nucleus through reactions like (5.16)-(5.24). The same is true of interactions in flight of strange particles of moderate energy. Thus we expect B mesons to be scattered by nuclei (with or without excitation of the nucleus) but \bar{B} mesons to be either scattered or absorbed.

As an application of this type of reasoning, let us consider the production of (Λ, θ) pairs by negative pions impinging on nuclei through the reaction

$$(5.25) \quad \pi^- + p \rightarrow \Lambda^0 + \theta^0.$$

In hydrogen gas, each Λ^0 should be accompanied by a θ^0 . (Of course each particle may have some decay modes that are invisible, such as the process $\Lambda^0 \rightarrow n + \pi^0$.) We may inquire also what happens in a block of lead (*). The Λ^0 and θ^0 may each suffer nuclear interactions before emerging. But in our theory, *neither the Λ^0 nor the θ^0 can be absorbed* [9]. Instead, the θ^0 may undergo charge exchange scattering and turn into a θ^+ , which may be undetectable as such in certain experiments. Thus we would find a lower ratio of θ^0 's to Λ^0 's in lead than in hydrogen gas. Actually, the Λ^0 , if sufficiently energetic, may undergo a sort of inelastic charge exchange scattering through the processes

$$(5.26) \quad \Lambda^0 + n \rightarrow \Sigma^- + p$$

$$(5.27) \quad \Lambda^0 + p \rightarrow \Sigma^+ + n.$$

Also, the Λ^0 may occasionally be trapped and form a hyperfragment. These processes may not be so important, though, as the charge exchange scattering of the θ .

5'5. *Consequences of the conservation of total isotopic spin.* — So far in this chapter we have concerned ourselves exclusively with consequences of the conservation of strangeness or, what is the same thing, the conservation of the z -component, I_z , of the total isotopic spin. We have postulated, however, that I^2 is conserved as well, although here corrections appear due to electromagnetic effects. We may now turn our attention to what follows from the fact that I^2 is a good quantum number for the strange particles.

One aspect of this situation has been investigated by DALITZ [10], who has listed the possible charge multiplets among the light hyperfragments, using our assignment of $I = 0$ to the Λ^0 -particle. He remarks, for example, that the existence of ${}^4\text{He}^*$, (composed of a Λ^0 , a neutron, and two protons), for

(*) Such an experiment has been performed by L. LEDERMAN (private communication).

which there is some experimental evidence, implies the existence of ${}^4\text{H}^*$ (composed of a Λ^0 , two neutrons, and a proton) with roughly the same binding energy.

Besides implying the existence of multiplets, the conservation of I^2 must yield selection and intensity rules such as we are familiar with among the ordinary particles. We shall mention at this point some of the more conspicuous ones involving the strange particles. In an obvious notation, we have

$$(5.28) \quad d\sigma(\pi^- + p \rightarrow \Lambda^0 + \theta^0) = d\sigma(\pi^+ + n \rightarrow \Lambda^0 + \theta^+)$$

or, what is perhaps more useful,

$$(5.29) \quad d\sigma(\pi^- + d \rightarrow \Lambda^0 + \theta^0 + n) + d\sigma(\pi^+ + d \rightarrow \Lambda^0 + \theta^+ + p).$$

Similarly, we have the relations

$$(5.30) \quad d\sigma(\pi^- + p \rightarrow \Sigma^- + \pi^+) = d\sigma(\pi^+ + n \rightarrow \Sigma^+ + \pi^-)$$

and

$$(5.31) \quad d\sigma(\pi^- + d \rightarrow \Sigma^- + \pi^+ + n) = d\sigma(\pi^+ + d \rightarrow \Sigma^+ + \pi^- + p).$$

Another such pair of equations concerns the absorption of negative K-particles:

$$(5.32) \quad d\sigma(K^- + p \rightarrow \Lambda^0 + \pi^0) = \frac{1}{2} d\sigma(K^- + n \rightarrow \Lambda^0 + \pi^-)$$

and

$$(5.33) \quad d\sigma(K^- + d \rightarrow \Lambda^0 + n + \pi^0) = \frac{1}{2} d\sigma(K^- + d \rightarrow \Lambda^0 + p + \pi^-).$$

For the production of (Λ, θ) pairs in nucleon-nucleon collisions we have the equation

$$(5.34) \quad d\sigma(n + d \rightarrow \Lambda^0 + \theta^0 + d) = d\sigma(p + d \rightarrow \Lambda^0 + \theta^+ + d)$$

and the inequality

$$(5.35) \quad d\sigma(n + p \rightarrow \Lambda^0 + \theta^0 + p) + d\sigma(n + p \rightarrow \Lambda^0 + \theta^+ + n) \geqslant \frac{1}{2} d\sigma(p + p \rightarrow \Lambda^0 + \theta^+ + p)$$

* * *

The author would like to thank the Institute for Advanced Study and its Director, Professor ROBERT OPPENHEIMER, for the opportunity of spending

the Spring semester of 1955 at the Institute, and also for sponsoring a trip to the Institute from Chicago in April, 1952, during the course of which most of the principal ideas contained in this paper were conceived after discussions with several Institute members, notably Dr. F. E. Low and Dr. T. D. LEE.

Thanks are due to the following physicists for fruitful conversation about the new particles during the last three years: Prof. T. D. LEE, Prof. A. PAIS, and the late Prof. E. FERMI.

The author is indebted to Dr. J. TEEM for a critical reading of the manuscript of this communication.

APPENDIX

Can other particles be accommodated in the scheme?

One is tempted to ask whether, if more particles are discovered, they can fit into the picture that we have developed. Let us ask in particular what possibilities there are for more particles *without introducing multiple charges*.

Among baryons we have already a doublet with $S = 0$ (\mathcal{N}), a singlet and a triplet with $S = -1$ (Λ and Σ), and a doublet with $S = -2$ (Ξ). The only other possibilities are evidently a singlet with $S = -3$, which we may call Ω^- , and a singlet with $S = +1$, which we have considered briefly in the text and called Z^+ . In order to be metastable, Z^+ must have a mass lower than the sum of the masses of \mathcal{N} and B ; similarly, the mass of Ω^- must be less than the sum of the masses of Ξ and \bar{B} . According to the rule $\Delta S = \pm 1$, the Z^+ would decay into a nucleon and a pion (or a proton and a γ -ray if there is not enough energy for a pion). The Ω^- would decay into a Ξ and a pion (or γ -ray). If there is enough energy, the Ω^- could also decay slowly into a \bar{B} and a Λ or Σ .

Among mesons we have already a triplet with $S = 0$ (π) and two pairs of doublets with $S = \pm 1$ (θ and $\bar{\theta}$, τ and $\bar{\tau}$). We might also have a pair of singlets with $S = \pm 2$ (say ω^+ and ω^-). For metastability, the mass of ω must be less than that of two B 's. The ω^+ would decay into a B plus a pion or γ -ray and the ω^- into a \bar{B} plus a pion or γ -ray.

It is an interesting exercise for the reader to ascertain under what circumstances the hypothetical Ω and ω particles could form metastable hyperfragments.

We have not discussed the possibility of duplication (that is, two multiplets with the same n , I and S) except in the case where nature has apparently forced it upon us (the case of the θ and τ). In order that the heavier of the duplicates be metastable against γ -decay to the lighter, special circumstances must prevail; for example, the θ and τ have a small mass difference and perhaps the transition is $0 \rightarrow 0$ as well.

REFERENCES

- [1] Much of the work to be presented is contained in the following publications:
M. GELL-MANN: *Phys. Rev.*, **92**, 833 (1953); M. GELL-MANN and A. PAIS: *Proceedings of the Glasgow Conference*, 1954, and in an unpublished note: M. GELL-MANN: *On the Classification of Particles* (circulated in preprint form, August, 1953). In these references, however, the proposals under discussion are mentioned only briefly and are sometimes buried in a mass of other material. Here they are treated alone and in some detail. Practically the same proposals have been put forward in Japan. See T. NAKANO and K. NISHIJIMA: *Prog. Theor. Phys.*, **10**, 581 (1953) and K. NISHIJIMA (to be published).
- [2] R. P. FEYNMAN and G. SPEISMAN: *Phys. Rev.*, **94**, 500 (1954).
- [3] Y. NAMBU, K. NISHIJIMA and Y. YAMAGUCHI: *Prog. Theor. Phys.*, **6**, 651 (1951); S. ONEDA: *Prog. Theor. Phys.*, **6**, 633 (1951); R. P. FEYNMAN: unpublished; A. PAIS: *Phys. Rev.*, **86**, 663 (1952).
- [4] G. C. WICK: *Accad. Lincei, Atti*, **21**, 170 (1935).
- [5] M. GELL-MANN and A. PAIS: *Phys. Rev.*, **97**, 1387 (1955).
- [6] W. B. FOWLER, R. P. SHUTT, A. M. THORNDIKE and W. L. WHITTEMORE: *Phys. Rev.*, **98**, 121 (1955).
- [7] M. G. K. MENON: private communication.
- [8] R. G. SACHS: Private communication.
- [9] A. PAIS and O. PICCIONI: *Phys. Rev.*, **100**, 1487 (1955).
- [10] R. H. DALITZ: *Phys. Rev.*, to be published.