Present Knowledge About the New Particles

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THIS discussion is divided into the following four sections: First an introduction to the subject, dealing mostly with generalities; then, a brief description of what seems at present to be established knowledge concerning the strange particles; thirdly, some topics currently under discussion by theoretical physicists; lastly, a question which has in the past year occupied a great deal of attention, namely, the identity of the K particles.

The discovery of the strange particles dates back to 1947, when Rochester and Butler[1] found, in a magnetic cloud chamber, V-shaped events in a penetrating shower induced by cosmic rays. This was followed in 1949 by the observation and identification[2] by Powell's group in England of the decay of the τ meson in electron sensitive emulsions. Experimental work on these strange particles, and others found later, rapidly expanded in the last few years. With the completion in 1953 of the cosmotron and in 1955 of the bevatron, experiments entered into a new era in which one can work with controlled beams of strange particles and in which one is able to make relatively accurate measurements on their interactions and decay. The scope and intensity of the experimental activities on this subject may be gauged from the fact that at the Brookhaven National Laboratory in the United States, 60% of the cosmotron time at present is devoted to the study of strange particles, the remaining time being divided between pion physics, radio chemistry, machine design, and other subjects.

What have we learned about these particles? We know the identity of quite a number of them; that is to say their masses, their charges, their lifetimes and decay modes. We know something about the processes by which they are produced. We could say that we know enough, so that there has emerged a common language among us in talking about them. We know enough to be able to plan controlled experiments which will tell us more about them. But the sum total of our knowledge goes very little beyond this. We are still confused by the identity of some of them, and we know very little about their spins and their parities. Above all, we do not have any idea or even any hint about the reason for their existence. Their relationship to each other and to the familiar particles do not seem to emerge in a simple pattern. Unlike Yukawa's π mesons, which fit into the physicist's picture of the world, the strange particles seem to be uncalled for, and unwanted. Do they presage the physicist's future understanding of small distances? Of the mass spectrum of particles? Or do they presage the breakdown of the concepts and laws that we have learned in the physics of nonstrange particles? These questions remain completely unanswered.

In view of our profound ignorance of what the whole subject is about, we must admit that we are very fortunate indeed to find in the experimental data many regularities, and many irregularities, which we hope may provide keys to a future understanding. We cherish such a hope mainly because of two facts: (a) The experiments consistently confirm a concept which we have had before, namely, that there is a natural classification of interactions into strong and weak interactions with very widely different orders of magnitude in their strengths. One senses that perhaps herein lies a very fundamental order of nature. (b) We recall that in the past, the concept of symmetry has played a very important role in physics. To quote a few examples: The theories of special and general relativity are founded upon such concepts of symmetry. Again, we could say that in essence the structure of the periodic table and therefore the properties of matter are largely determined by the isotropy of space, or in other words, by the symmetry of nature under space rotations. The prediction of the existence of the positron and of the antiproton were based upon the symmetry of nature under Lorentz transformations. Now it is observed that symmetries, and the related concepts of quantum numbers and selection rules are very much involved in the regularities and irregularities in the behavior of the new particles. We may therefore hope that the study of them will lead to a further understanding of nature.

To go on to the second topic, let us briefly outline our knowledge about the new particles. The well-established law of conservation of the number of nucleons requires that all particles have a "heavy particle quantum number" N. The nucleons have $N=1$. The pions, photons, electrons, neutrinos, and μ mesons have $N=0$. The antinucleons have $N=-1$. It is customary to call the strange particles with $N=1$ hyperons, those with $N=0$ mesons. Table I lists the experimental knowledge about the hyperons. Table II lists that about the positive and neutral mesons. Negative mesons are expected to behave like the charge conjugates of the positive ones, and they seem to do just that. They are therefore omitted from the table. In these tables, I have given numbers in round figures. More complete and detailed information with

[1] G. D. Rochester and C. C. Butler, Nature **160**, 855 (1947).
[2] Brown *et al.* Nature **163**, 82 (1949).

TABLE I. Experimental knowledge about hyperons.

Hyperon	Decay product	Q	Mean life
Λ^0	$p+\pi^-$	37 Mev	3.7×10^{-10} sec
Σ^+	$n+\pi^+$	110	$\sim1\ \times10^{-10}$
	$p+\pi^0$		
Σ^0	$\Lambda^0+\gamma$		short
Σ^-	$n+\pi^-$	110	$\sim2\ \times10^{-10}$
Ξ^-	$\Lambda^0+\pi^-$	~67	$\sim1\ \times10^{-10}$

references can be found in the various review compilations.[3]

In addition to tabulating the strange particles, we must say something about their interactions. There seem to be three kinds of interactions, the strong interactions, the electromagnetic interactions and the weak interactions. By the weak interactions we mean those responsible for the decay of the strange particles, for beta decay, for μ-meson decay, for π-meson decay, and for the μ-meson nucleon interaction. The reason why one feels some confidence in such a classification is that if one makes a rough dimensional analysis of the coupling strengths, one finds that the π-meson interactions and the production processes for the strange particles have intensities of around 1 to 10^{-1}; the electromagnetic interaction, as is well known, has strength 10^{-2}; and the weak interactions have intensities ranging from 10^{-12} to 10^{-14}. The wide gap separating the weak interactions from the other two forms such a striking and consistent pattern that one cannot but feel that there is some fundamental reason for it. A characteristic feature of the strange particles is that their production seems to fall into the class of strong interactions and their decays into the class of weak interactions. The practical manifestation of the weakness of the decay interaction is the fact that the strange particles all have lifetimes of the order of 10^{-10} sec or longer; i.e., more than 10^{+13} cy of nuclear time.

Let us write down the various invariance properties of these interactions besides invariance with respect to space time transformations. For all interactions it is found that the number of nucleons is conserved, and that charge is conserved. If we however limit ourselves to the strong and the electromagnetic interactions, we find that there is another conservation law, which one refers to as the conservation of "strangeness." If one makes the assignments of strangeness as follows:

$$n,\ p,\ \pi^+,\ \pi^0,\ \pi^- \qquad S=0$$
$$K^-,\ \bar{K}^0,\ \Lambda^0,\ \Sigma^+,\ \Sigma^0,\ \Sigma^- \qquad S=-1$$
$$\Xi^- \qquad S=-2$$
$$K^+,\ K^0 \qquad S=+1$$

then the experimental production data all conform to the statement that the strong interactions conserve strangeness. Thus, for example, in

$$\pi^-+p\rightarrow K^0+\Lambda^0,$$
$$n+n\rightarrow\Lambda^0+\Lambda^0,$$

the first reaction is expected to be a strong interaction, and the second one should be forbidden as a strong interaction. These indeed have been borne out experimentally. Finally, if we confine ourselves to the strong interactions only, the isotopic spin seems to be a good quantum number, just as in pion physics and in nuclear physics for light nuclei. One of the components, I_3, is related to the charge Q, the heavy particle number N, and the strangeness quantum number S in the following way:

$$I_3=Q-\frac{N}{2}-\frac{S}{2}.$$

The concept of strangeness has proved to be extremely fruitful in the past year or two, and although we do not understand the origin of this conservation law, nor do we know what new additional selection rules and quantum numbers will turn up in the future, it seems fair to say that strangeness conservation is here to stay.

As to theoretical problems of current interest: first there is the question of $\theta^0-\bar{\theta}^0$, (or $K^0-\bar{K}^0$). It was pointed out a few years ago that since the θ^0 particle has a strangeness of $+1$, its antiparticle $\bar{\theta}^0$ must have strangeness -1 and must therefore be a different particle. The decay of these particles was then expected to exhibit rather queer properties. This is of great interest, because these properties of the decay were predicted purely on the basis of symmetry principles. An experimental test of these predictions is in progress. Another problem which has been occupying a number of physicists is the question of the possible methods for the determination of the spins of the various strange particles Then there is the question: just how do the weak interactions violate strangeness? Also there is the study of hyperfragments, which are nuclei with Λ^0 particles bound in them It has been pointed out that an examination of the binding energies of light hyperfragments will yield some information about the Λ^0-nucleon force such as its spin dependence Lastly there

TABLE II. Experimental knowledge about neutral and positive mesons.

Meson	Decay product	Mass	Mean life	Fraction of all K^+
θ°	$\pi^++\pi^-$	See below	1.7×10^{-10} sec	
$\theta_2{}^\circ$	$?+?+?$			
$K_{\pi3}{}^+\equiv\tau^+$	$2\pi^++\pi^-$	All K^+ and K° have mass	All K^+ about	6%
$\tau^{+\prime}$	$2\pi^\circ+\pi^+$	$\sim966m_e$	$1\ \times10^{-8}$ sec	2%
$K_{\pi2}{}^+$	$\pi^++\pi^\circ$			25%
$K_{\mu2}{}^+$	$\mu^++\nu$			60%
$K_{\mu3}{}^+$	$\mu^++\nu+\pi^\circ$			$\sim$3%
$K_{e3}{}^+$	$e^++?+?$			$\sim$5%

[3] See, e. g., A. M. Shapiro, Revs. Modern Phys. 28, 164 (1956).

is the subject of the so-called "freak" particles, which have turned up periodically, and which do not seem to fit into any established categories These and other questions have been discussed in the literature

I now turn to the last topic, namely, the question of the identity of the K particles Interest in this subject started when it was pointed out that by studying the decay of the $K_{\pi 3}^+$, also known as the τ^+ meson, into three charged π mesons, it is possible to conclude something about its spin and parity Let me give you a simple example of the kind of arguments involved. Suppose one of the π mesons resulting from the decay of a τ meson is very slow, so that one may assume that it comes out in an s state relative to the center of mass of the other two π mesons. What can one conclude under these circumstances? Well the remaining two pions will be in one of the states $0^+, 1^-, 2^+, \cdots$, because the pions are spinless, and their intrinsic parities add up to 'even', so that the spin and parity of the two pion system are identical with those of the orbital part of their wave function. The extra π meson is odd, and contributes no angular momentum; we can therefore conclude that the spin and parity of the 3 pions together can only be 0^- or 1^+ or $2^- \cdots$. Since spin and parity are conserved in any process, the τ meson spin parity also must be $0^-, 1^+, 2^-$, etc. The $K_{\pi 2}$ by the same argument can only be $0^+, 1^-, 2^+, \cdots$. Therefore we may conclude that if ever the τ meson is found to decay into three pions one of which is slow, the $K_{\pi 2}$ and τ cannot be the same particle. Of course, the analysis is not quite so simple, because there is always the question: how slow is "slow" for the decay pion? To investigate this problem, the distribution of the momenta of the decay products of the τ has been plotted in a triangular plot and the full distribution studied against the various possible spin parity assignments for τ. With the one-thousand or so points available at the present moment the general opinion is that the τ is not the same particle as the $K_{\pi 2}^+ \equiv \theta^+$.

However it will not do to jump to hasty conclusions. This is because experimentally the K mesons seem all to have the same masses and the same lifetimes. The masses are known to an accuracy of say from 2 to 10 electron masses, or a fraction of a percent, and the lifetimes are known to an accuracy of say 20%. Since particles which have different spin and parity values, and which have strong interactions with the nucleons and pions, are not expected to have identical masses and lifetimes, one is forced to keep the question open whether the inference mentioned above that the τ^+ and θ^+ are not the same particle is conclusive. Parenthetically, I might add that the inference would certainly have been regarded as conclusive, and in fact more well founded than many inferences in physics, had it not been for the anomaly of mass and lifetime degeneracies.

There has been in the past year a number of speculations concerning the reason for this anomaly. There was the suggestion that the equality of masses of two particles, say τ and θ, which have the same spin but opposite parity might come about in the following way: consider the process $\theta^+ \rightarrow p + \bar{\Lambda}^0 \rightarrow \theta^+$: the θ^+ particle virtually dissociates into a proton and an anti-Λ^0, which then recombine. Such a process contributes to the mass of the θ^+ particle, and does so appreciably, because all the interactions involved are strong interactions. Consider the same process for the τ^+ particle: $\tau^+ \rightarrow p + \bar{\Lambda}^0 \rightarrow \tau^+$. Because of its different parity the contribution to the mass of τ^+ from this virtual dissociation will be different (as the virtual particles will be in different orbital states relative to one another). After looking at this for a while, it appears that the only way for the contribution to be equal is that there exist two Λ^0 particles: Λ_1^0 and Λ_2^0, which have opposite parities, so that the process $\theta^+ \rightarrow p + \bar{\Lambda}_1^0$ has its counterpart in $\tau^+ \rightarrow p + \bar{\Lambda}_2^0$ with the same orbital motion. The proposal has therefore been made that there may exist another symmetry operation called "parity conjugation," C_p, which leaves the strong interactions invariant, and which has the property of interchanging θ and τ. Also it is assumed that there are two kinds of Λ^0's, and two kinds of Σ's, and that they go into one another under the operation of C_p.

It can easily be shown that the weak interactions which violate strangeness conservation cannot be invariant under C_p. In fact since Λ_1^0 and Λ_2^0 do not have the same parity, they decay in quite different ways into their final products. For example, the final product of the decay

$$\Lambda^0 \rightarrow \pi^- + p$$

would in one case be in even relative orbital states, and in the other case be in odd relative orbital states, and therefore there is no reason why the two Λ^0's should have the same lifetimes. This is also true for the θ and the τ. Thus the parity conjugation concept does not explain the equality of lifetimes.

An obvious test whether this speculation is correct is to see whether there do indeed exist such "parity doublets." One could for example look for evidences for two lifetimes for the Λ^0's or the Σ's. Another way of detecting parity doublets is through the interference of the two decay modes of the two members of a parity doublet This will work if the mass difference between the two members of the doublet is very small, say of the order of 10^{-5} ev. In that case, let us consider an experiment currently being done in Berkeley: the capture of K^- particles in a hydrogen bubble chamber, and single out the process

$$K^- + p \rightarrow \Sigma^- + \pi^+.$$

What is seen in the experiment is a K^- coming to rest in the chamber, and a π^+ and a Σ^- coming out. The Σ^- is relatively short-lived, and most of them decay before coming to rest, as follows

$$\Sigma^- \rightarrow \pi^- + n.$$

Let us now analyze the angular distribution of the decay particles (say the pion) under the assumption that the spin of Σ is $\frac{1}{2}$. The angle in question is the angle θ between the decay π^- and the line of flight of Σ^- in the rest system of Σ^-. We can analyze the spin into "up" and "down" components along the direction of motion of the Σ particle, and after doing this, let us make a reflection in the plane containing the lines of flight of the Σ^- and the π^- coming from its decay. Since under this reflection the spin flips (to see this picture the spin as a rotating top, so that under the reflection the sense of rotation changes, and so does the spin), and it is assumed that under a reflection the interactions are invariant, the Σ^- must have equal populations of up and down spins. In other words it is unpolarized. The angular distribution with respect to θ must then be spherically symmetric for ordinary Σ^-. However if the Σ^- does not have a definite parity, i.e. if it consists of a Σ_1^- and a Σ_2^- having opposite parities, then under an inversion they still both flip the spin. But due to their different parities they acquire a 180° phase difference between them, and therefore they would interfere, giving a forward-backward asymmetry (i.e., an asymmetry between θ and $\pi-\theta$,) a conclusion that can be experimentally tested.

With the existence of parity doublets of nearly equal masses one expects some very interesting phenomena. A beam of spin $\frac{1}{2}$ particles is usually described by four real parameters: its intensity, and a polarization vector which is the average spin of the beam. For a beam of spin $\frac{1}{2}$ particles with parity doublet structure the description is vastly more complex, because you now need four real intensities, one for the intensity of the particles of one parity, one for that of the other parity, and two for the real and the imaginary parts of the interference intensity. Also, whereas only one space vector is needed to describe the polarization in the usual case, now four space vectors are needed to describe the polarization: namely one describing the average spin of one parity one for that of the other, and two describing the interference polarization. The interference intensities are pseudoscalars instead of scalars, and the interference polarization vectors are vectors instead of axial vectors. The recognition of these transformation properties leads immediately to a number of conclusions about interference effects of parity doublets. These can all be subjected to experimental tests, and we may hope to have a clarification of the situation in the next few months.

A much more drastic thought has been advanced regarding this problem, namely the observation that both the mass identity and the lifetime identity can be understood if parity is not conserved in the decay. There need then be only one K particle, which has a definite parity upon production, but which can decay into various parities. This again is a proposal which can be subjected to experimental tests. The first question which comes to mind is: is the present evidence for parity conservation good enough to rule out such a proposal? One finds that the most accurate experiment to date, which tests and confirms the conservation of parity in strong and electromagnetic interactions, is the measurement of the electric dipole moment of the neutron which was found to be accurately zero. This experiment, though extremely accurate, is however not sufficient to yield a conclusive statement about whether the weak interactions also conserve parity, because the weak interactions are just too weak to influence the experiment. Furthermore, an examination of the tremendous bulk of knowledge about the beta interaction shows that to date there is no evidence there either for or against parity conservation in the weak interactions.

Fortunately, one can propose experiments which can test parity conservation in weak interactions, experiments which essentially test whether the weak interactions show a preference of one-sensed screw to the other. To give a typical example, consider the process

$$\pi^- + p \rightarrow \Lambda^0 + K^0$$

and examine the π^- coming from the decay of the Λ^0,

$$\Lambda^0 \rightarrow p + \pi^-.$$

Let us now ask whether the decay product π^- has an average component of momentum perpendicular to the plane of the incident π^- and the Λ^0, this plane being defined in a particular way, say, by having the Λ^0 direction always to the right of the incoming π^-. If there is such an average component, it would define a sense of screw, and its existence would indicate a non-conservation of parity in one of the processes involved, which would have to be the decay process, since the strong interaction is invariant under inversion. Another way of putting it is this: if the momentum of the incident π^- is $\mathbf{k}_1$, that of the Λ^0 is $\mathbf{k}_2$, and that of the outgoing π^- is $\mathbf{k}_3$, what we are looking for is the distribution with respect to the sign of $(\mathbf{k}_1 \times \mathbf{k}_2) \cdot \mathbf{k}_3$. This expression changes sign under space inversion. Unequal distribution with respect to its sign therefore means violation of invariance under inversion.

Another experiment, which is perhaps more easily done, is to study the angular distribution of the beta decay of an oriented nucleus. What is involved is to see whether there is an asymmetry with respect to the sign of $\boldsymbol{\sigma} \cdot \mathbf{K}$, where $\mathbf{K}$ is the electron momentum, and $\boldsymbol{\sigma}$ the spin of the nucleus. I understand that this experiment is currently being done at Columbia, and at the National Bureau of Standards.

When one opens the question of whether parity is or is not conserved for the weak interactions, one must also raise the question of the validity of the other conservation laws. Let us list the various conservation laws: they are the conservation of energy, momentum, angular momentum, parity, the invariance under time reversal (T) and the invariance under charge conjugation (C). Energy and momentum seem to be conserved in the weak interactions. The analysis of the conservation of angular momentum in weak interactions is more complex than the corresponding analysis of parity conservation, because parity conservation can be violated in only one way, whereas angular momentum conservation can be violated in a large number of ways. To my knowledge this analysis has not been carried out. Let us now consider T and C. A closer look at these conservation laws shows that there is no proof that these are conserved in weak interactions. One might at first think that the equality of the lifetimes of the π^+ and π^-, or the μ^+ and μ^-, which are charge conjugate particles, says something about this matter. But an examination of this problem shows that the lifetimes will be equal to the lowest order in the weak coupling constant (which is to an order of accuracy of 10^{-12}, and therefore essentially infinite accuracy) merely on the assumption of invariance under orthochronous Lorentz transformations (i.e., Lorentz transformations in which there are neither space nor time inversions). Because of this, the absolute invariance under C must be regarded as experimentally not proved.

Let me conclude with the point that if parity is indeed not strictly conserved, there would be a preference for either right handedness or left handedness in the universe, and this would appear to be unaesthetic. One may however observe that if one's definition of invariance is generalized, the question may appear in a quite different light. Let me give a simple example which T. D. Lee and I have speculated about: suppose that parity is not conserved, i.e., that there is a difference on going from a left-handed to a right-handed coordinate system. It may turn out, however, that by simultaneously going from one coordinate system to the other *and* switching to the anti-world, i.e., replacing π^+ by π^-, protons by antiprotons, etc., symmetry is regained. This merely shows that there is a richness in the structure of these symmetry laws which we are quite far from comprehending.

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On the Origins of Cosmic Rays

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IN 1954, Professor Einstein once remarked that there were two easily observable phenomena that, in his opinion, showed a deep fundamental lack in our knowledge of the physical world. These, he said, were the cosmic rays, and the terrestrial magnetic field. We can be all but sure today that he was wrong in that intuition, but he was expressing exactly that feeling which theoretical physicists have had for many decades, which somehow justifies the inclusion of topics like this one in a program on theoretical physics.

It is my opinion that they no longer quite belong in such a discussion. They have to do neither with the fundamental laws of physics nor with the difficult problems of applying the fundamental laws to relatively simple systems. On the contrary, both of these phenomena (which turn out to have the same fundamental origin) are examples of application of good old classical physics to a world of atomic materials, using nothing but the still unknown solutions to the nonlinear equations of magnetohydrodynamics.

The beginning of the path toward an explanation was shown to us perhaps 20 years ago when Fermi, Vallarta, and others began their series of investigations into the effect of the earth's field upon the cosmic rays which has led us now into a nearly complete understanding of, say, the latitude effect. The idea was gained, and given quantitative support, that the cosmic rays were not given and immutable, something whose origin could not be approached because they were so far beyond ordinary experience. This idea was aided by that kind of theoretical result, but most especially by the facility with which experimental physicists have *made* cosmic rays. For they have the same problems and the same difficulties that are encountered in nature in the large.

The study of the origin of cosmic rays (while we do not yet have a fully understandable, and certainly not a quantitative model) is no longer devoted mainly to the interpretation of empirical evidence obtained from properties of the cosmic rays themselves, but must draw as well from general astrophysical means of observation. These wider results are for the first time sharply relevant this year, and therefore it is perhaps appropriate to summarize very briefly what sort of path one can take for a tentative understanding of this extraordinary and interesting phenomenon. I intend to describe just one path; I know that there are many; I know that there are even people in the audience who have produced other paths for the explanation. The one I shall point out is the most coherent we have today. It is still a model;