Model of the Strong Couplings

MURRAY GELL-MANN
Physics Department, California Institute of Technology, Pasadena, California
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An attempt is made to construct a crude field theory of hyperons and K particles, which are assumed to have spin $\frac{1}{2}$ and spin 0, respectively. The parity of Λ is defined to be plus. Some preliminary experimental evidence is adduced in support of parity plus for Σ. It is further argued that Λ and Σ are coupled to π with roughly the same coupling constant as in the $\pi-N$ case, while the coupling of K to baryons is weaker.

A model of the strong couplings is suggested that incorporates these features. The very strong (VS) pion interactions are completely symmetrical in the baryons, and would leave them all degenerate in the absence of the moderately strong (MS) interactions of K. These last lead to the mass differences among baryons and to the production and absorption of K particles. The MS coupling constants must be determined by experiment, but the VS interactions are exactly specified.

With the MS couplings treated in lowest approximation, it is possible to relate any matrix element for K and hyperon reactions to a corresponding matrix element in the theory of nucleons and pions. Thus in the processes $\bar{K}+p\rightarrow\pi+\Lambda$ and $\bar{K}+p\rightarrow\pi+\Sigma$ it is expected that in the final state the analog of the (3/2,3/2) resonance of the $\pi-N$ system will be observed.

It may be, as Wigner has suggested, that the equality of pion couplings for the baryons is somehow related to the conservation of baryons, and that the analogy with electromagnetic coupling is instructive.

I. INTRODUCTION

DESPITE the scarcity of experimental information now available on the strong interactions of K particles and hyperons, it is perhaps worthwhile to speculate about the nature of these couplings, and to see to what extent experiments already performed may guide such speculations.

In studying the properties of mesons and baryons at one or two Bev, we may already be exploring a highly unfamiliar world, in which the characteristics of space-time are altered, or causality is violated over short intervals, or particles are bound to one another with binding energies comparable to their masses to form apparently "elementary" systems.

Yet in constructing a detailed theory of the strong couplings, we encounter the difficulty that we have as yet no language except that of field theory in which to express ourselves; and the present language and methods of field theory are surely not adequate to describe a really unfamiliar situation. In any case, there are grave doubts about the applicability of conventional local field theory to phenomena at energies greater than a Bev:

(1) If electrodynamics is used to make a crude calculation of n-p and $\pi^{+}-\pi^{0}$ mass differences, a cutoff is indicated in the neighborhood of 1 Bev.[1]

(2) The consistency of strong-coupling local field theories at these energies (or lower) has been challenged by some physicists,[2] who claim that negative probabilities are predicted.

(3) If a "fundamental length" really exists at which present concepts fail, it would be most natural to place it near the nucleon Compton wavelength, and to try, in a future theory, to relate the masses of mesons and baryons to it.

Still, there remains the possibility that the concepts and methods of conventional field theory may be useful to us in describing the new particles, at least as an approximation and over a limited range of energy. It is the purpose of this work to explore that possibility in the light of the few data now available. We shall try to see to what extent the new may be like the old.

In accordance with this point of view, we assume that the spin of K is zero and that of each hyperon (Λ, Σ, Ξ) is $\frac{1}{2}$. The spins of Λ, Σ, and K are now being determined experimentally, especially by angular correlations. Preliminary results[3] are in accord with spin $\frac{1}{2}$ for Λ and spin 0 for K, but there are some indications that the spin of Σ may be $\frac{3}{2}$. If this last should turn out to be true, our speculations here will have little value.

Parity, although not conserved by the weak interactions, seems to be conserved by the strong ones, and we shall assume so. The parity of Λ relative to the nucleon N is not defined, since it could be measured only by a decay process like $\Lambda^0\rightarrow p+\pi^-$, which is weak and presumably need not conserve parity. We may, however, arbitrarily assign parity $+$ to Λ, and measure the parities of Σ and K relative to it. (In a similar way, the parity of the proton relative to the neutron, which is not really uniquely defined, is called $+$ and the parity of the charged pion is measured relative to this assignment.) We adopt, as usual, the convention that the parity of N is $+$. We are left, then, with four possibilities: Σ_+K_+, Σ_+K_-, Σ_-K_+, and Σ_-K_-, where the subscript indicates the parity. We ignore, for the time being, couplings of Ξ.

It is now obvious what to do to construct a simple field-theoretic model for each of these cases. For each

[1] R. P. Feynman and G. Speisman, Phys. Rev. **94**, 500 (1954).

[2] See, for example, Landau, Abrikosov, and Halatnikov, Nuovo cimento, Suppl. **1**, 80 (1956).

[3] Private communication from Dr. A. H. Rosenfeld on the work of several groups.

of the Yukawa-type processes allowed by charge independence, we introduce an appropriate scalar or pseudoscalar interaction (depending on the relative parity involved) and a coupling parameter g. Thus in the case $\Sigma_+ K_-$ our interaction Lagrangian density is

$$\mathcal{L}=g_{N\pi}\mathcal{P}_{N\pi}+g_{\Lambda\pi}\mathcal{P}_{\Lambda\pi}+g_{\Sigma\pi}\mathcal{P}_{\Sigma\pi}+g_{\Lambda K}\mathcal{P}_{\Lambda K}+g_{\Sigma K}\mathcal{P}_{\Sigma K}, \quad (1)$$

where the pseudoscalar couplings $\mathcal{P}$ are defined as follows (we use the symbol for a particle to denote the field operator that destroys it):

$$\mathcal{P}_{N\pi}=i[(\bar{p}\gamma_5 p-\bar{n}\gamma_5 n)\pi^0+\sqrt{2}(\bar{p}\gamma_5 n\pi^+ +\bar{n}\gamma_5 p\pi^-)], \quad (2a)$$

$$\mathcal{P}_{\Lambda\pi}=i[\bar{\Sigma}^0\gamma_5\Lambda^0\pi^0+\bar{\Sigma}^+\gamma_5\Lambda^0\pi^+ +\bar{\Sigma}^-\gamma_5\Lambda^0\pi^-] +\text{Herm. conj.}, \quad (2b)$$

$$\mathcal{P}_{\Sigma\pi}=i[(\bar{\Sigma}^+\gamma_5\Sigma^+ -\bar{\Sigma}^-\gamma_5\Sigma^-)\pi^0+(\bar{\Sigma}^0\gamma_5\Sigma^- -\bar{\Sigma}^+\gamma_5\Sigma^0)\times\pi^+ +(\bar{\Sigma}^-\gamma_5\Sigma^0-\bar{\Sigma}^0\gamma_5\Sigma^+)\pi^-], \quad (2c)$$

$$\mathcal{P}_{\Lambda K}=i[\bar{p}\gamma_5\Lambda^0 K^+ +\bar{n}\gamma_5\Lambda^0 K^0]+\text{Herm. conj.}, \quad (2d)$$

$$\mathcal{P}_{\Sigma K}=i[\bar{p}\gamma_5\Sigma^0 K^+ -\bar{n}\gamma_5\Sigma^0 K^0+\sqrt{2}\bar{n}\gamma_5\Sigma^- K^+ +\sqrt{2}\bar{p}\gamma_5\Sigma^+ K^0]+\text{Herm. conj.} \quad (2e)$$

In the other cases, we substitute wherever parity demands it a scalar interaction $\mathcal{S}$ for the pseudoscalar one $\mathcal{P}$ (replace $i\gamma_5$ by 1).

In the subsequent sections we shall see that preliminary experimental results, if interpreted according to this type of theory, seem to point to the case $\Sigma_+ K_-$ (or perhaps $\Sigma_+ K_+$) with $g_{\Lambda\pi}^2\approx g_{N\pi}^2$ and $g_{\Lambda K}^2$ and $g_{\Sigma K}^2$ rather smaller. A fairly specific model with these properties will then be suggested on grounds of symmetry.

II. USE OF EXPERIMENTAL EVIDENCE

In predicting the results of a field theory with strong coupling and comparing these results with experiment, we must try, as much as possible, to avoid the pitfalls that were encountered in the case of the nucleon-pion interaction. The lesson we have learned from that case may perhaps be summarized in this way: a qualitative feature of the relativistic theory that also appears in a simple static model may be believed, while an intrinsically relativistic prediction is doubtful. We shall use this criterion and, in a general way, analogy with the $\pi-N$ situation in order to choose experiments that really distinguish one of our theories from another.

The most instructive experiment in this regard seems to be the study of the reactions $\gamma+p\rightarrow\Lambda^0+K^+$ and $\gamma+p\rightarrow\Sigma^0+K^+$ near threshold. Let us discuss the first of these. If the ideas we are using here have any validity at all, then this process should be sensitive to the parity of the K and to the coupling constant $g_{\Lambda K}^2/4\pi$. In particular, if K is pseudoscalar, the analogy with the pion seems to be excellent. We recall that for the reaction $\gamma+p\rightarrow\pi^+ +n$ there is s-wave production near threshold with total cross section

$$\sigma_\pi\approx\frac{2\pi}{m_N^2}\frac{e^2}{4\pi}.\frac{g_{N\pi}^2}{4\pi}\frac{V_\pi}{c}, \quad (3)$$

where V_π is the pion velocity. For the reaction $\gamma+p\rightarrow K^+ +\Lambda^0$, the same phenomenon should occur, with a cross section

$$\sigma_K\approx\frac{\pi}{m_N^2}\frac{e^2}{4\pi}\frac{g_{\Lambda K}^2}{4\pi}\frac{V_K}{c}\approx 10\mu\text{b}\times\frac{g_{\Lambda K}^2}{4\pi}\frac{V_K}{c}. \quad (4)$$

If $g_{\Lambda K}^2/4\pi$ were of the same magnitude as $g_{N\pi}^2/4\pi\approx 15$, then the cross section for photoproduction of K at $V_K/c=\frac{1}{3}$ would be ≈ 50 μb. Now only the most preliminary experiments have been done so far, but they seem to rule out a cross section this large.[4] Thus, we conclude that if K is pseudoscalar the coupling strength $g_{\Lambda K}^2/4\pi$ is considerably smaller than $g_{N\pi}^2/4\pi$, perhaps of the order of unity.

Of course, even with a pseudoscalar K, it is possible that the small cross section is due to a cutting-off of electrodynamics or to some other breakdown of conventional concepts, but such explanations are not in the spirit of this work.

The reason that such emphasis has been placed on discarding the possibility of a large pseudoscalar coupling of N to K and Λ is that just such a coupling is required if the exchange of a K particle is to be responsible for the attraction between Λ and N in hyperfragments.

This hypothesis has been investigated by Wentzel,[5] who finds (using perturbation theory):

(1) If K is scalar, the force between Λ and an α particle or heavier nucleus is repulsive, contrary to observation.

(2) If K is pseudoscalar, the force between Λ and any light nucleus is attractive and strongly favors antialignment of the Λ spin and the nuclear spin.

The latter alternative is consistent with our present knowledge of the hyperfragments,[6] but the coupling strength required to give binding of Λ is at least as great as that of the pion-nucleon interaction (the potential is like the neutron-proton potential due to charged pions alone, but has a shorter range, corresponding to m_K^{-1} instead of m_π^{-1}).

We must therefore look for a different mechanism for the binding of Λ to nuclei. The only other simple scheme available is that of Lichtenberg and Ross[7] and of

[4] Clegg, Ernstene, and Tollestrup, Bull. Am. Phys. Soc. Ser. II, 2, 235 (1957); Peterson, Roos, and Terman, Bull. Am. Phys. Soc. Ser. II, 2, 235 (1957); P. L. Donoho and R. L. Walker, Bull. Am. Phys. Soc. Ser. II, 2, 235 (1957).

[5] G. Wentzel, Phys. Rev. **101**, 835 (1956).

[6] R. Dalitz, *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics, 1956* (Interscience Publishers, New York, 1956).

[7] D. Lichtenberg and M. Ross, Phys. Rev. **103**, 1131 (1956) and private communication.

Dallaporta and Ferrari,[8] who suggest the exchange of two pions between Λ and N, with Λ turning into Σ in between. According to their calculations, this fails to give attraction if Σ has negative parity, but if Σ has positive parity it gives an attractive force that favors the antialignment of Λ spin and nuclear spin, as possbility (2) above.

Once more the required coupling constant must be of the order of $g_{N\pi}^2/4\pi \approx 15$, but here we are concerned with $g_{\Lambda\pi}^2/4\pi$, which, for all we know, may be this large.

We have concluded, then, that the Σ must have positive parity if our type of model is to work that $g_{\Lambda\pi}^2/4\pi \approx g_{N\pi}^2/4\pi$, and that hyperfragments have Λ spin and nuclear spin antialigned.

Further, we may say that if K is pseudoscalar, then $g_{\Lambda K}^2/4\pi \ll g_{N\pi}^2/4\pi$, and the exchange of a K particle plays a minor role in the binding of hyperfragments.

We have not, however, excluded the possibility that K is scalar. There is some slight evidence against this at the moment:

Let us consider the scattering of K by N, which should proceed most simply through the couplings $g_{\Lambda K}$ and $g_{\Sigma K}$, each in second order. In the case of scalar coupling, the scattering at low energies does not involve virtual states with pairs, as in pseudoscalar coupling. Therefore we may place some confidence in the qualitative predictions of the perturbation theory, which we would *not* do for pseudoscalar coupling, since we were led astray in the case of s-wave pion-nucleon scattering. But with scalar coupling, the perturbation theory predicts attraction of K^+ and p in the s state. Preliminary experiments,[9] on the other hand, seem to indicate a repulsion at low energies.

We shall thus suppose, in what follows, that K is pseudoscalar, with $g_{\Lambda K}^2/4\pi \ll g_{N\pi}^2/4\pi$, but we may bear in mind the possibility that it is scalar.

There is perhaps some evidence that $g_{\Lambda K}^2/4\pi \ll g_{N\pi}^2/4\pi$ independently of the K parity. Experiments even at quite high energies[10] seem to show that the production of K particles is considerably less frequent than that of pions.

An interesting experiment has been proposed by Dalitz,[6] which tests both the parity of the K particle and the spins of hyperfragments. One looks for the process $K^- + He^4 \rightarrow \pi^0 + {}_{\Lambda}H^4$ using slow K^-. If it is found, then the well-known decay ${}_{\Lambda}H^4 \rightarrow \pi^- + He^4$ should frequently follow. One then looks at the angular distribution of π^- relative to ${}_{\Lambda}H^4$ (say this angle is θ). We consider two possibilities for the spin of ${}_{\Lambda}H^4$: if the $\Lambda - N$ forces tend to antialign spins, as we have argued they do, then the spin is 0; if not, the spin is 1. The conservation of angular momentum and the conservation of parity by the strong interactions then imply:

(1) If K is scalar and ${}_{\Lambda}H^4$ has spin 0, the process $K^- + He^4 \rightarrow \pi^0 + {}_{\Lambda}H^4$ is forbidden.

(2) If K is pseudoscalar and ${}_{\Lambda}H^4$ has spin 0, the process is fully allowed and the decay of ${}_{\Lambda}H^4$ is isotropic.

(3) If K is pseudoscalar and ${}_{\Lambda}H^4$ has spin 1, the process is forbidden for K in an s state but may proceed from K in a p state; the decay has the distribution $\sin^2\theta$. If the K particles are not stopped, one should also observe a correlation between the K-particle direction of motion and the normal to the plane of π^- and ${}_{\Lambda}H^4$ motions, of the form $\cos^2\varphi$.

(4) If K is scalar and ${}_{\Lambda}H^4$ has spin 1, the process is allowed for K in an s state, with a $\cos^2\theta$ distribution for the decay, and also for K in a p state, with an essentially isotropic distribution of the decay when the K particles are stopped. If the K particles are not stopped, the decay is nonisotropic with respect to the direction of motion of K to the extent that p waves are involved.

The speculations of this section have led us to expect case (2) or possibly case (1).

III. A SIMPLE MODEL

Our arguments from experimental evidence are admittedly weak, but if we take them seriously they hint at a rather definite picture of the strong couplings, and this picture seems to have some intrinsic merit. We draw on our previous discussion for these two points:

(1) There is a strong pseudoscalar coupling of the pion to Λ and Σ with $g_{\Lambda\pi}^2/4\pi \approx g_{N\pi}^2/4\pi$.

(2) The coupling constant $g_{\Lambda K}^2/4\pi$ is smaller than $g_{N\pi}^2/4\pi$.

We now consider a point of view recently discussed by Schwinger,[11] and reminiscent of some earlier work of Pais.[12] Suppose that there are two classes of strong couplings, very strong (VS) and moderately strong (MS). Then we may draw an analogy between VS and MS couplings on the one hand and strong and electromagnetic couplings on the other. The strong couplings possess a symmetry (charge independence) that is destroyed by the electromagnetic ones. Charge multiplets, which would be completely degenerate in the absence of electromagnetism, are split when the charges are "turned on." According to the analogy the VS couplings should possess a still higher symmetry that is destroyed by the MS couplings. If the MS couplings are "turned off," degeneracies should show up among the elementary particles, with the charge multiplets assembled into "supermultiplets." The MS couplings would then split these into the observed charge multi-

[8] N. Dallaporta and F. Ferrari (to be published).

[9] See, for example, Baldo-Ceolin, Cresti, Dallaporta, Grilli, Guerriero, Merlin, Salandin, and Zago (to be published).

[10] *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics, 1956* (Interscience Publishers, New York, 1956).

[11] J. Schwinger, Phys. Rev. **104**, 1164 (1956).

[12] A. Pais, *Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics, 1955* (Interscience Publishers, Inc., New York, 1955). See also A. Salam and J. C. Polkinghorne, Nuovo cimento **2**, 685 (1955).

plets. It is possible to suppose that all the known baryons, Ξ, Σ, Λ, and N, form a supermultiplet, symmetrically coupled by the VS interactions and degenerate as far as they are concerned, but unsymmetrically coupled by the MS interactions and split by them into the observed multiplets Ξ, Λ, Σ, and N.

It is now very tempting to say that the pion couplings are VS and the K-particle couplings MS. All the baryons are symmetrically coupled to the pion field with a coupling constant ≈ 15. The K-particle couplings are weaker and less symmetric in the baryons although still charge independent.

We are now led to a practically unique theory of the pion interactions. We must somehow couple Ξ, Σ, and Λ to the pion field in the same way that nucleons are coupled. For Ξ, the solution is obvious. Just as the nucleon is coupled through the interaction

$$\mathcal{P}_{N\pi}=i[(\bar{p}\gamma_5 p-\bar{n}\gamma_5 n)\pi^0+\sqrt{2}(\bar{p}\gamma_5 n\pi^+ +\bar{n}\gamma_5 p\pi^-)], \quad (2a)$$

so Ξ must be coupled through

$$\mathcal{P}_{\Xi\pi}=i[(\bar{\Xi}^0\gamma_5\Xi^0-\bar{\Xi}^-\gamma_5\Xi^-)\pi^0 +\sqrt{2}(\bar{\Xi}^0\gamma_5\Xi^-\pi^+ +\bar{\Xi}^-\gamma_5\Xi^0\pi^-). \quad (5)$$

For Σ and Λ, since they are not isotopic spin doublets, we must resort to a trick. We define $Y^0\equiv(\Lambda^0-\Sigma^0)/\sqrt{2}$ and $Z^0\equiv(\Lambda^0+\Sigma^0)/\sqrt{2}$ and then write the coupling

$$\begin{aligned}\mathcal{P}=i[(\bar{\Sigma}^+\gamma_5\Sigma^+-\bar{Y}^0\gamma_5 Y^0)\pi^0 &+\sqrt{2}(\bar{\Sigma}^+\gamma_5 Y^0\pi^+ +\bar{Y}^0\gamma_5\Sigma^+\pi^-)]\\ +i[(\bar{Z}^0\gamma_5 Z^0-\bar{\Sigma}^-\gamma_5\Sigma^-)\pi^0 &+\sqrt{2}(\bar{Z}^0\gamma_5\Sigma^-\pi^+ +\bar{\Sigma}^-\gamma_5 Z^0\pi^-)], \quad (6)\end{aligned}$$

which obviously treats (Σ^+,Y^0) and (Z^0,Σ^-) on the same footing as we have treated (p,n) and (Ξ^0,Ξ^-). If we now substitute for Y^0 and Z^0 their definitions in terms of Σ^0 and Λ^0, we find at once that

$$\mathcal{P}=\mathcal{P}_{\Sigma\pi}+\mathcal{P}_{\Lambda\pi}, \quad (7)$$

where $\mathcal{P}_{\Sigma\pi}$ and $\mathcal{P}_{\Lambda\pi}$ are the two charge-independent couplings we introduced in Eq. (2). The complete VS interaction may then be written in the form

$$g_{N\pi}\mathcal{P}_{N\pi}+g\mathcal{P}+g_{\Xi\pi}\mathcal{P}_{\Xi\pi}. \quad (8)$$

Since the VS interaction is to leave all the baryons degenerate, we must have

$$g_{N\pi}^2=g^2=g_{\Xi\pi}^2. \quad (9)$$

The signs of $g_{N\pi}$ and $g_{\Xi\pi}$ relative to g are now the only points at issue. They are physically important, since they determine the signs of, say, the second-order nuclear potentials acting between Σ and N, N and Ξ, etc. Yet they do not matter for the degeneracy of the baryons. On grounds of symmetry we shall suppose that they are both plus and that the VS interaction has the form

$$g(\mathcal{P}_{N\pi}+\mathcal{P}_{\Lambda\pi}+\mathcal{P}_{\Sigma\pi}+\mathcal{P}_{\Xi\pi}) \quad (10)$$

with $g^2/4\pi\approx 15$. We may, however, still retain this general picture if the signs should turn out otherwise.

Now the MS couplings of the K meson are harder to pin down since the requirement of asymmetry is a weaker one than that of symmetry. There are four constants to be determined: the coefficients $g_{\Lambda K}$ and $g_{\Sigma K}$ defined in Eqs. (1) and (2) and the analogous coefficients $h_{\Lambda K}$ and $h_{\Sigma K}$ of the interactions

$$\mathcal{P}_{\Lambda K}'\equiv i[\bar{\Xi}^-\gamma_5\Lambda^0\bar{K}^+ +\bar{\Xi}^0\gamma_5\Lambda^0\bar{K}^0]+\text{Herm. conj.}, \quad (11)$$

and

$$\mathcal{P}_{\Sigma K}'\equiv i[\bar{\Xi}^-\gamma_5\Sigma^0\bar{K}^+ -\bar{\Xi}^0\gamma_5\Sigma^0\bar{K}^0+\sqrt{2}\bar{\Xi}^0\gamma_5\Sigma^+\bar{K}^+ +\sqrt{2}\bar{\Xi}^-\gamma_5\Sigma^-\bar{K}^0]+\text{Herm. conj.} \quad (12)$$

We are supposing that K is pseudoscalar.

The mass differences[13] of the hyperons give important information about the MS coupling constants if our picture is correct. An investigation of this question will be described elsewhere.

Let us discuss here, however, some consequences of our theory of the pion couplings. The most striking feature, of course, is the global symmetry of the interaction. We must be careful, however, in using this symmetry to predict the results of experiments, since the MS interactions, and especially the rather large mass differences they induce, will often mask the symmetry of the VS couplings.

Nevertheless, let us be simple-minded and try a first approximation in which baryon mass-differences are neglected and processes involving K mesons are described by taking the MS couplings as perturbations in the lowest order that gives an effect.

For example, take the processes $K^-+p\to\pi+\Lambda$ and $K^-+p\to\pi+\Sigma$. In our approximation they are described by matrix elements

$$\langle\pi\Lambda|ig_{\Lambda K}\bar{\Lambda}^0\gamma_5 p+ig_{\Sigma K}(\bar{\Sigma}^0\gamma_5 p+\sqrt{2}\bar{\Sigma}^-\gamma_5 n)|p\rangle$$

and

$$\langle\pi\Sigma|ig_{\Lambda K}\bar{\Lambda}^0\gamma_5 p+ig_{\Sigma K}(\bar{\Sigma}^0\gamma_5 p+\sqrt{2}\bar{\Sigma}^-\gamma_5 n)|p\rangle.$$

(The particles labeling the states are physical particles, with complete pion clouds, and the matrix elements are therefore by no means trivial.) Let us examine one of these terms in detail, say $\langle\pi^0\Lambda^0|ig_{\Sigma K}\bar{\Sigma}^0\gamma_5 p|p\rangle$. In terms of Y^0 and Z^0, we have

$$\frac{ig_{\Sigma K}}{2}\{\langle\pi^0 Z^0|\bar{Z}^0\gamma_5 p|p\rangle-\langle\pi^0 Y^0|\bar{Y}^0\gamma_5 p|p\rangle +\langle\pi^0 Y^0|\bar{Z}^0\gamma_5 p|p\rangle-\langle\pi^0 Z^0|\bar{Y}^0\gamma_5 p|p\rangle\}. \quad (13)$$

[13] If the mass differences are calculated in the lowest order of the MS couplings, it is found that $(m_N+m_\Xi)/2=(3m_\Sigma+m_\Lambda)/4$. Experimentally, the first quantity is about 190 Mev above the nucleon mass, while the second is about 235 Mev above it. This discrepancy may be small enough to account for by higher order effects, even with MS coupling constants of the order of unity.

Looking at our VS interaction [Eqs. (2), (6), and (10)], we see that Z^0 and Y^0 belong to different worlds, so to speak. There is no VS mechanism by which the operator $\bar{Y}^0$ can create a Z^0 particle, or vice versa. Thus the third and fourth terms in (13) vanish in our approximation. For the first two terms, we have another very simple result. Since our VS interaction couples the pion to the pair Σ^+Y^0 and to the pair $Z^0\Sigma^-$ in exactly the same fashion as to the pair pn, we may write in our approximation

$$\langle \pi^0 Y^0 | \bar{Y}^0 \gamma_5 p | p \rangle = \langle \pi^0 n | \bar{n} \gamma_5 p | p \rangle, \tag{14}$$

and

$$\langle \pi^0 Z^0 | \bar{Z}^0 \gamma_5 p | p \rangle = \langle \pi^0 p | \bar{p} \gamma_5 p | p \rangle. \tag{15}$$

We have reduced our problem of K-particle absorption essentially to a problem in the theory of pions and nucleons. The complete evaluation of the matrix elements for K absorption in terms of nucleon and pion matrix elements may be carried out in the same way. Let us comment here on some qualitative features.

First of all, we have two free parameters $g_{\Lambda K}$ and $g_{\Sigma K}$, but it is to be hoped that experiments on K-particle photoproduction will soon determine these. Moreover, arguments based on baryon mass differences and on K-particle scattering may already give us significant information, as will be discussed in subsequent work.

Next, we must be careful, even in our approximation, in saying that the matrix elements for K-particle processes are really *predicted* by our formulas. The matrix elements in the pion-nucleon theory to which they are referred are neither reliably calculated nor experimentally measured: the matrix elements describe situations that are not on the energy-shell for pion processes, and some of the matrix elements describe the absorption of a fictitious pion with $I=0$. Nevertheless, a combination of theoretical analysis and extrapolation of experimental results should give us estimates of the needed matrix elements.

One qualitative feature is particularly interesting. When low-energy K^- particles are absorbed in the p-state, they give a pion-hyperon system also in a p state and with a kinetic energy in the neighborhood of 100–200 Mev. Since in our theory pion-hyperon scattering is directly related to pion-nucleon scattering, we may observe the analog of the famous $J=\frac{3}{2}$, $I=\frac{3}{2}$ resonance (in this case a $J=\frac{3}{2}$, $I=1$ resonance).

A survey, based on our model, of hyperon and K meson phenomena is in progress and should yield estimates of all or most quantities of experimental interest. The likelihood of success may not be great, but at least there will be formulas with which to compare the experimental results.

IV. GENERAL REMARKS

Supposing that the model we have presented has elements of truth, we may add the following remarks:

(1) The symmetry properties of the model may be correct even though the use of field theory is unjustified. For this reason, an analysis purely in terms of the symmetry group of the theory is in order. It can be done in a mathematically elegant manner, but that approach has not been followed here for the sake of greater clarity.

(2) It is interesting to look at the speculations of Wigner[14] and Schwinger[11] and others about the connection between coupling constants and conservation laws. We are tempted strongly to say that the possession by all baryons of the same pionic coupling is associated with the conservation of baryons, just as the possession by charged particles of the same electromagnetic coupling is associated with conservation of charge. The analogy is not perfect, of course, since the quantity that is conserved microscopically is always a four-vector current density; in the case of electromagnetism, it is just this current density that is coupled to photons, while for the baryons it is a different, nonconserved pseudoscalar density that is coupled to the pions. Still, the analogy may have value.

On the basis of this analogy, Wigner[14] predicted in 1952 that all baryons would have the same coupling to the π field.

(3) The role of strangeness and its relation to the charge and the z component of isotopic spin are still mysterious. Perhaps the elucidation of the manner in which the MS couplings reduce the symmetry of the baryons will throw light on this question.

(4) Problems involving the polarization of the vacuum by pions must be investigated. In particular, the calculation of the rate of the decay $\pi^0 \to 2\gamma$ must be revised. To the extent that baryon masses are equal, the amplitudes for decay through the pairs $\bar{p}, p$ and $\bar{\Sigma}^+, \Sigma^+$ cancel the amplitudes for decay through $\bar{\Sigma}^-, \Sigma^-$ and $\Xi^-, \bar{\Xi}^-$. Thus the decay rate is reduced, which may help agreement with observation. Such a situation was discussed by Kinoshita.[15]

It is a pleasure to acknowledge the value of discussions with Professor R. F. Christy and Professor R. P. Feynman.

Note added in proof.—In the model described here a mass difference between Σ^+ and Σ^- can arise only from the combined effect of the MS and electromagnetic interactions; it is therefore very hard to reconcile the model with the observed large mass difference of $\sim$4 Mev.

[14] E. P. Wigner, Proc. Natl. Acad. Sci. U. S. **38**, 449 (1952).
[15] T. Kinoshita, Phys. Rev. **94**, 1384 (1954).