Possible Model for Strong Interactions*

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A model is considered for the strong interactions of pions, K mesons, nucleons, and hyperons. A system of interactions is postulated and several features of the experimental situation are discussed from the new viewpoint. No restrictions are placed upon the coupling parameters involved other than that they characterize a system of strongly interacting particles.

IN this note we shall discuss a possible model for the strong interactions of pions, K mesons, nucleons, and hyperons. At the outset it should be said that the proposed scheme rests primarily on several suggestive features of the present experimental situation. Our comments will be couched in the language of conventional field theory, as the latter supplies a framework suitable to the discussion. We shall first outline the model, making clear its points of similarity to and departure from the recent models of Gell-Mann[1] and Schwinger,[2] and then we shall discuss the experimental features that underlie it.

Under the simplest assumptions for the above system of strongly interacting particles, namely that the fermions have spin one-half and the bosons have spin zero and that there is no parity doubling of the strange particles, the number of interaction terms of the Yukawa type which may be present in the Hamiltonian is eight,[3] each term being characterized by a coupling strength. The model of Gell-Mann[1] reduces this number of coupling parameters to five by introducing the hypothesis of global symmetry for the pion-baryon interactions. This requires that the coupling of a pion to cascade particles and to Σ particles as well as the coupling of a pion to a Σ and a Λ be of the same strength as the well-known pion-nucleon coupling. The mass differences are attributed in this theory to the K-meson couplings which are assumed to be somewhat weaker than the pion-baryon interactions. In the original theory of Schwinger,[2] the three pion-hyperon interactions enumerated above were not considered to be primary, leaving only the pion-nucleon interaction in this group. In addition, a four-dimensional symmetry imposed upon the Σ triplet and the Λ on the one hand, and the cascade particle and nucleon doublets on the other, required the couplings of these particles with K mesons to be of equal strength. Finally, a linear interaction between a pion and two K mesons of opposite parity was considered.[4] The number of coupling parameters was thus three. In this theory it is hypothesized that, after the K-meson interactions have separated the cascade particle-nucleon quartet from the Σ-Λ quartet, the pion-nucleon interaction serves to depress the nucleon mass below that of the cascade particle, while the π-K interaction separates the Σ and Λ masses. It is to be noted that each of these theories consider as primary the pion-nucleon interaction as well as the four K meson-baryon couplings. Starting at this point, with the five coupling parameters thus introduced, we have addressed ourselves to the question of how much else must be added to this interaction Hamiltonian in order to arrive at a scheme which may be capable of making contact with the early experimental situation, as well as a scheme of some predictive power. One answer to this question is that of Gell-Mann, namely the introduction of three primary pion-hyperon interactions in conjunction with the hypothesis of global symmetry, with the consequent predictions for the behavior of pion-hyperon systems in analogy with the pion-nucleon system. In this note we would like to take an alternative viewpoint which avoids the explicit introduction of these three terms and hence the need for the broad hypothesis of global symmetry. We would like instead to consider the consequences of adding a single additional interaction term to the Hamiltonian, this being a boson-boson interaction term of the form $K^\dagger K\pi^2$ (here the symbol for the particle denotes its field operator and the isotopic indices are suppressed). Interaction terms quadratic in two boson fields have existed as a consequence of general principles for some time in quantized field theories. One instance occurs when the Lagrangian for the free pion field is made gauge-invariant in the presence of the electromagnetic field. The term is of the form $e^2A_\mu A^\mu\pi^\dagger\pi$ where e is the electric charge, A_μ is the four-vector potential and π and $\pi^\dagger$ destroy (create) and create (destroy) positive (negative) pions. respectively. A similar term exists with the pion field replaced by the K-meson field. An interaction term of the form $\lambda\pi^4$ is present in the relativistic theory of

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1 M. Gell-Mann, Phys. Rev. **106**, 1296 (1957).
2 J. Schwinger, Phys. Rev. **104**, 1164 (1956).
3 See, for example, R. H. Dalitz, Eight Lectures on Strong Interactions of Strange Particles, given at Brookhaven National Laboratory, Summer, 1957 (unpublished).
4 This interaction was considered in the light of early angular distributions in associated production phenomena by M. Goldhaber, Phys. Rev. **101**, 433 (1956), and also by S. Barshay, Phys. Rev. **104**, 853 (1956). The latter note also considered the pion-hyperon couplings in connection with these angular distributions.

pion-nucleon phenomena as an infinite counterterm to renormalize the divergent pion-pion scattering. Whether a finite part of this term contributes a real pion-pion effect is a question for future refined experiments to investigate.[5] These are, of course, not Yukawa-type interactions, and one may take the view that Yukawa interactions should be considered as primary, even when the number of such terms requires a simplifying hypothesis to make the theory manageable. We would like to take an alternative view that a nonlinear boson-boson interaction of the form suggested may be an important part of a field-theoretic scheme of strong interactions, with significant physical consequences.

We shall now consider a model involving the following couplings: a pion with nucleons, a K meson with a nucleon and a Λ, a K meson with a nucleon and a Σ, and a $K^\dagger K\pi^2$ interaction. In addition we consider the possibility of the couplings of a K meson to a cascade particle and a Λ and to a cascade particle and a Σ. We shall be concerned with the first four terms above in considering the present energy range of the experiments. We wish to impose no restriction on this system of coupling strengths other than that they be characterized as strong ($g^2/4\pi\sim 1$) to very strong ($g^2/4\pi\sim 10$), the one established very strong interaction being the pion-nucleon interaction. The form of the interactions is determined by the conservation of isotopic spin. (We shall not consider at this time the possibility of a "weak" violation of this conservation law in strange-particle interactions.[6-8] By the term "weak" here, we mean that the apparent multiplet structure of the Σ-particle masses, for example, must not be altered by this violation.) It is evident that the mass structure of the baryons may be hypothesized in our scheme in the same spirit as in the models of Gell-Mann and Schwinger. The K-meson couplings will split up the cascade particle, Σ, Λ, and nucleon masses and the pion-nucleon interaction may further depress the nucleon mass below that of the hyperons. It is interesting to note that if we do not consider the effect of the possible K meson-cascade particle couplings, we see that the K meson-Σ-nucleon coupling, $g_{K\Sigma N}$, must not be exactly equal to the K meson-Λ-nucleon coupling, $g_{K\Lambda N}$, if the scheme is to be capable of accounting for the Σ-Λ mass difference. We shall make use of the fact in discussing K^+-nucleon scattering that it is just the equality $g_{K\Sigma N}^2=g_{K\Lambda N}^2$ which implies vanishing charge exchange scattering via the Yukawa-type interactions. In further comment on the mass differences we note that the $K^\dagger K\pi^2$ interaction term introduces the appealing possibility of accounting for the K meson-pion mass difference through their mutual quadratic interaction.[9]

Let us now consider several aspects of the present experimental situation from the proposed viewpoint. We start with K^+ scattering by nucleons. A striking point appears in connection with the ratio of charge exchange to noncharge exchange scattering. A recent experiment[10] sets an upper limit of 1/10 for K^+ mesons of energies from 30 to 65 Mev. The most probable number of charge exchange events observed in this experiment is zero. In this energy region the slow variation[10,11] of the total cross section with K^+ energy implies that the scattering is largely in the S wave. We now point out that two general characteristics of K-meson scattering proceeding through the pion-nucleon interaction and the $K^\dagger K\pi^2$ term are (a) the scattering is predominantly in the S wave whether the K meson be a scalar or pseudoscalar particle, and (b) the scattering amplitudes for the states of isotopic spin zero and one are equal and hence the charge-exchange scattering vanishes. Now for K^+ energies above 100 Mev the charge-exchange to non-charge-exchange ratio appears to have risen to about 0.2,[11,12] and also a tendency of the total cross section to increase implies the advent of P-wave scattering. From the proposed viewpoint this is readily understandable in terms of the advent of "direct" scattering through the couplings of the K meson to the nucleon and the Λ and to the nucleon and the Σ. Such scattering would have the familiar P wave producing spin dependence at the absorption and emission vertices (for intermediate states with a positive energy hyperon) if the K meson is pseudoscalar (scalar) and the Λ and Σ are of positive (negative) parity relative to the nucleon. Only if the two couplings involved here satisfied $g_{K\Sigma N}^2=g_{K\Lambda N}^2$ would the charge exchange scattering vanish (in the limit $m_\Sigma=m_\Lambda$). We have noted above that this is possibly an unlikely circumstance in view of the Σ-Λ mass difference. We have looked at the possible sign of the lowest order field-theoretic static potential between a K meson and a nucleon arising from the $gK^\dagger K\pi^2$ interaction. It is obvious that this potential depends in sign upon the sign of the coupling parameter g. For positive g, the potential is repulsive; this result is independent of the parity of the K meson. The repulsive behavior is favored by present experimental results.[12]

We now consider K^--proton interactions. From our viewpoint the K^- should also elastically scatter in the S wave at low energies through the $K^\dagger K\pi^2$ interaction. However, there is more to the story here, since the absorptive processes such as $K^-+p\rightarrow\Lambda^0+\pi^0$, which are very probable real processes for low-energy K^-, will occur virtually and will influence the elastic and charge-exchange scattering. For example, we may have the following sequence contributing to the charge-

[5] I would like to thank Dr. Oreste Piccioni for a discussion on this point.

[6] Brown, Glaser, Meyer, Perl, Vander Velde, and Cronin, Phys. Rev. **107**, 906 (1957).

[7] J. J. Sakurai, Phys. Rev. **107**, 908 (1957).

[8] S. Barshay, Phys. Rev. **107**, 1454 (1957).

[9] This point was commented upon by Professor Schwinger (see session IX in reference under footnote 12).

[10] Hoang, Kaplan, and Cester, Phys. Rev. **107**, 1698 (1957).

[11] Widgoff, Pevsner, Davis, Ritson, Schluter, and Henri, Phys. Rev. **107**, 1430 (1957).

[12] *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, 1957* (Interscience Publishers, Inc., New York, 1957), Session VI.

exchange scattering $K^- + p \to K^- + \pi^0 + p \to \Lambda^0 + \pi^0 \to \bar{K}^0 + \pi^0 + n \to \bar{K}^0 + n$. An interesting feature of the absorption of low-energy K^- mesons by protons leading to the states $\Sigma^- + \pi^+$ and $\Sigma^+ + \pi^-$ is that experiment[13] indicates that the former process is more frequent than the latter. The production of Σ^- may occur through the direct process $K^- + p \to K^- + \pi^+ + n \to \pi^+ + \Sigma^-$ and also through the intermediary of the $K^\dagger K\pi^2$ interaction as follows:

$$K^- + p \to K^- + \pi^+ + n \to \pi^+ + K^- + n \to \pi^+ + \Sigma^-.$$

The latter mechanism will strongly favor the production of a pion-Σ system in an S wave. The observed angular distribution is at present flat.[12,13] On the other hand, the Σ^+ production would occur in the following sequence without the intermediary of the $K^\dagger K\pi^2$ interaction: $K^- + p \to \Lambda^0 \to \bar{K}^0 + n \to \bar{K}^0 + \pi^- + p \to \pi^- + \Sigma^+$. The ratio of the Σ^- to the Σ^0 produced in the absorption of low-energy K^- mesons by protons through the intermediary of the $K^\dagger K\pi^2$ interaction alone would be about 4/1.

Several interesting features of the model appear if we examine several strange-particle processes at the higher energies. Consider pion production in a K^+-nucleon collision. The threshold on a free nucleon is at about 220-Mev incident K^+ kinetic energy. It might be expected that the possibility of the process proceeding in second order through the pion-nucleon and $K^\dagger K\pi^2$ interactions would enhance this cross section. A rough perturbation estimate for the process $K^+ + p \to K^+ + \pi^+ + n$ at 300 Mev indicates an enhancement factor in the differential cross section, $d\sigma/dE_\pi$, with E_π, the pion kinetic energy, equal to 25 Mev, of about $5[g_{KK\pi^2}{}^2/(g_{K\Sigma N}{}^2 + g_{K\Lambda N}{}^2)]$ for scalar K mesons and about $20[g_{KK\pi^2}{}^2/(g_{K\Sigma N}{}^2 + g_{K\Lambda N}{}^2)]$ for pseudoscalar K mesons. It is of interest that this process has been observed already at Brookhaven.[14] The event occured in emulsion at 280-Mev incident K^+ kinetic energy and has been interpreted as $K^+ + n \to K^+ + \pi^- + p$. A more detailed study of pion production by K mesons will be given by the author at a later date. Also of interest is the associated production in proton collisions near 1 Bev. A strong S-wave component will be contributed by the process proceeding through the $K^\dagger K\pi^2$ interaction as follows:

$$\pi^- + p \to \pi^- + \pi^+ + n \to K^0 + \bar{K}^0 + n \to K^0 + \Lambda^0.$$

The high-energy cross section for a black sphere of radius $(m_K + m_\pi)^{-1}$ is about 3 mb. That the associated production cross sections should tend to a constant area of very strong interaction[15] as the incident pion energy is raised would seem a reasonable consequence of this model. It would be interesting to see how often the processes $\pi + N \to \pi + K + Y$ and $K + \bar{K} + N$ occur above 1 Bev.

Before making our concluding remarks, we must mention that a two-pion exchange between a Λ particle and a nucleon will proceed through the intermediary of the $K^\dagger K\pi^2$ interaction. The range of this force may be $\sim (2m_\pi)^{-1}$, i.e., somewhat longer than that arising from the exchange of a single K meson. We do not believe that the status of the theory of hyperfragment binding at present precludes such mechanisms.[3]

We would like to summarize here the viewpoint of this model. First, it is felt that a nonlinear boson-boson interaction of a form that has been present before in quantum field theories may be an important part of the system of strong interactions characterizing pions, K mesons, nucleons, and hyperons. In the present experimental energy range, an interaction quadratic in the pion and K meson fields, the pion-nucleon interaction, and interactions of a K meson with a nucleon and a Σ, and with a nucleon and a Λ, constitute a system (not necessarily a closed system) of strong interactions which may be utilized in making a contact with several interesting features of the experiments, as we have seen. We do not wish to make any broad assumptions about relationships or equalities among these primary couplings. There are many things that we might try to calculate inside this system if we knew how to handle strongly coupled fields. For example, there is the scattering in the pion-hyperon systems. It is also very tempting to examine pion-nucleon S-wave scattering proceeding through the intermediary of the $K^\dagger K\pi^2$ interaction. The magnitude of the low-energy scattering cross section from a black sphere of radius $\sim (2m_K)^{-1}$ is about 5 mb and this is the order of magnitude of the low-energy pion-nucleon S-wave scattering. However, this mechanism does not give the isotopic splitting. There must be more to the story; presumably the intermediate nucleon pair state, which is of about the same range, must also contribute to the scattering. It appears that there are features of the model that are suggestive of some of the present observations. It may be that the departure of the scheme from strict adherence to Yukawa-type interactions may be a more general feature than the specific model discussed.

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[13] Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, University of California Radiation Laboratory Report 3775, July, 1957 (unpublished).

[14] G. T. Zorn and B. Sechi Zorn (private communication). I would like to thank Dr. G. T. Zorn for informing me of this event and for a helpful discussion.

[15] L. R. Leipuner and R. K. Adair, Phys. Rev. **109**, 1358 (1958).