PHYSICAL REVIEW VOLUME 101, NUMBER 1 JANUARY 1, 1956

Compound Hypothesis for the Heavy Unstable Particles. II

M. GOLDHABER
Brookhaven National Laboratory, Upton, New York*
(Received August 19, 1955)

The compound hypothesis for hyperons and heavy mesons is restated, modifying an earlier assumption on the isotopic spin of θ^0. θ mesons and $\bar{\theta}$ mesons (antiparticles) are assumed to have isotopic spin $T=\frac{1}{2}$, as proposed by Gell-Mann. The total number of heavy mesons (θ mesons minus $\bar{\theta}$ mesons) is conserved in strong interactions (fast reactions). The fundamental reaction is thus pair creation of $\theta+\bar{\theta}$, with θ mesons free and $\bar{\theta}$ mesons either free or bound to nucleons ($\mathfrak{N}$). Hence $\mathfrak{N}+\bar{\theta}$ can form $T=0$ and $T=1$ multiplets which are identified with the Λ^0 singlet and the Σ triplet, respectively. The facts known about hyperons, associated production, and interaction of heavy mesons with nucleons are consistent with our assumptions. A discussion of T-multiplets among hypernuclei is given. Some experiments which may throw new light on the compound hypothesis are discussed.

I. INTRODUCTION

THE rapid progress of our knowledge of the heavy unstable particles makes it desirable to restate the "compound hypothesis" for hyperons and heavy mesons[1] with some necessary modifications. Because of its great simplicity, this hypothesis appears to us worth pursuing as long as it holds out hope of a deeper theoretical approach; in the meantime, it is at least a help in classifying hyperons and processes involving hyperons and heavy mesons (production and absorption). Most of the difficulties with which the hypothesis has met in its previous form can be traced back to the assumption of an isotopic spin $T=0$ for the θ^0 particle. This assumption could not account for the fact that, while some kinds of associated production were observed (e.g., $\Lambda^0+\theta^0$, Σ^-+K^+), others were not (e.g., $\Lambda^0+\Lambda^0$, Σ^++K^-, K^++K^+). Also, it did not explain the preferential production of slow K^+-mesons as compared with slow K^--mesons by cosmic rays as well as at Cosmotron or Bevatron energies.[2] If, however, we adopt the suggestion of Gell-Mann,[3] of Nakano and Nishijima,[4] and of Pais,[5] elaborated further by Gell-Mann and Pais,[6] that the θ mesons have isotopic spin $T=\frac{1}{2}$ and that their antiparticles, $\bar{\theta}$ mesons, exist, we can modify the compound hypothesis in a very natural manner which apparently removes disagreement with the well-established facts. In its present form the hypothesis is closely related to various other classification schemes.[3–9]

II. DEFINITIONS AND ASSUMPTIONS

(1) It is useful to have a word describing a particle which, in strong interactions, is produced only in association with at least one other particle. We propose the word *dion* for such a particle. It is probable that all known hyperons and heavy mesons are dions. Though this is not well established in all cases, there are no known contradictions to this assumption.

(2) The θ family is assumed to be a new fundamental family of particles, to be added to those previously established (nucleons, pions, etc.) without any attempt, at the present time, to explain the new family in terms of other particles. From their decay schemes ($\theta^0\to\pi^+ +\pi^-$, $\theta^+\to\pi^++\pi^0$), and from spin conservation, it follows that θ mesons are bosons.

(3) Following Gell-Mann[3,4] we shall assume for the θ family, even though we are dealing with bosons properties which are similar to those assumed for the nucleon family (the nucleons and antinucleons). Thus we have θ mesons (θ^+, $T_z=+\frac{1}{2}$; θ^0, $T_z=-\frac{1}{2}$) and $\bar{\theta}$ mesons ($\bar{\theta}^0$, $T_z=+\frac{1}{2}$; θ^-, $T_z=-\frac{1}{2}$), with θ^0 and $\bar{\theta}^0$ assumed to be distinct at creation.[10]

(4) We shall assume that the θ family is characterized by a new quantum number, which we shall call here d (dionic quantum number), and which we shall define as $d=+1$ for θ mesons, and $d=-1$ for $\bar{\theta}$ mesons. It may be that d represents some new "dionic charge," which is conserved in strong interactions, i.e., $\Delta d=0$ for fast reactions. We shall use d in the following con-

* Under the auspices of the U. S. Atomic Energy Commission.
1 M. Goldhaber, Phys. Rev. **92**, 1279 (1953).
2 For recent general references to the experimental material and theoretical ideas on heavy mesons and hyperons see, e.g., Proceedings of the Fourth and Fifth Rochester Conference on High Energy Physics, 1954 and 1955 (Interscience Publishers, Inc., New York City, 1954, 1955); Proceedings of the Padua Congress, Nuovo cimento **12**, Suppl. No. 2, 1954; papers by C. C. Butler and L. LePrince-Ringuet in the Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics (Pergamon Press, London, 1955); B. Rossi, Notes of lectures given at International Summer School, Varenna, 1954 [Nuovo cimento **2**, Suppl. No. 1, 163 (1955)]; R. W. Thompson, Progress in Cosmic Ray Physics, Vol. 3 (to be published); Dilworth, Occhialini, and Scarsi, Ann. Rev. Nuc. Sci. **4**, 271 (1955); H. A. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson, and Company, Evanston, 1955), Vol. 2, Sec. 51; R. E. Marshak, Report on Pisa Conference, 1955, NYO-7138 (unpublished).
3 M. Gell-Mann, Phys. Rev. **92**, 833 (1953).
4 T. Nakano and K. Nishijima, Progr. Theoret. Phys. (Japan) **10**, 581 (1953); K. Nishijima, Progr. Theoret. Phys. (Japan) **12**, 107 (1954).
5 A. Pais, Proc. Natl. Acad. Sci., U. S. **40**, 484, 835 (1954).
6 M. Gell-Mann and A. Pais, Proceedings of 1954 Glasgow Conference on Nuclear and Meson Physics (Pergamon Press, London, 1955), p. 342; A. Pais, Proceedings of Fifth Annual Rochester Conference (Interscience Publishers, Inc., New York, 1955), p. 131.
7 D. C. Peaslee, Phys. Rev. **86**, 127 (1952), **91**, 446 (1953), and Nuovo cimento **12**, 943 (1954).
8 R. G. Sachs, Phys. Rev. **99**, 1576 (1955).
9 M. Levy and R. E. Marshak, Nuovo cimento **12**, Suppl. No. 2, 253 (1955).
10 Their later fate, in the free state, may be complicated if θ and $\bar{\theta}^0$ are not simple particles, but each a particle mixture, as discussed by M. Gell-Mann and A. Pais [Phys. Rev. **97**, 1387 (1955)] and A. Pais and O. Piccioni [Phys. Rev. **100**, 1487 (1955)].

siderations only to enumerate the number of θ mesons ($d>0$) or $\bar{\theta}$ mesons ($d<0$) present.[11] For weak interactions, i.e., the slow decay processes of θ mesons, which are $\sim 10^{12}$ times slower than the fast reactions, it follows that $\Delta d = \pm 1$.

(5) We further introduce the specific assumption that there is an attractive interaction between nucleons and $\bar{\theta}$ mesons, sufficiently strong to lead to compound formation (hyperons), whereas the interaction between nucleons and θ mesons might be repulsive or less strongly attractive. Such an asymmetry in interaction is not inconsistent with the assumed particle and antiparticle nature of the heavy mesons, and, as is shown below, leads to a consistent picture of associated production.

While it is true that many of the over-all conclusions which we deduce are the same as those which follow from less specific classification schemes[6,8] we should like to give our deductions here in concise form, not only for the sake of completeness, but also because of the simple way in which they are visualized on the compound hypothesis. More detailed experiments and theoretical considerations may, however, decide between the different ideas. In the concluding remarks we shall discuss some possible distinctions between the point of view of compounds and the less specific schemes.

III. EXISTING HYPERONS AND ASSOCIATED PRODUCTION

From our assumptions it follows that members of the θ family of particles are made in pairs, $\theta+\bar{\theta}$ ($\Delta d=0$), with θ mesons free and $\bar{\theta}$ mesons either free or bound to nucleons. When nucleons of isotopic spin $T=\frac{1}{2}$ bind $\bar{\theta}$ mesons, also of isotopic spin $T=\frac{1}{2}$, four states will be formed ($n+\theta^-$, $p+\theta^-$, $n+\bar{\theta}^0$, $p+\bar{\theta}^0$) of isotopic spins $T=0$ and $T=1$ and $d=-1$; these may be very naturally identified with the known hyperons: $\Lambda^0(T=0)$ and the Σ family ($T=1$), respectively. Σ^+ and Σ^- are then states of $p+\bar{\theta}^0$ and $n+\theta^-$, respectively, whereas, Λ^0 and Σ^0 are mixed $n+\bar{\theta}^0$ and $p+\theta^-$ states. It may be worth remarking that the members of the Σ triplet need not have exactly the same mass. A mass difference may not only exist between Σ^0 and $\Sigma^\pm$, but also between Σ^+ and Σ^- because of their different structure: The difference in mass which exists between n and p, and possibly between θ^- and $\bar{\theta}^0$, combined with a difference in electromagnetic effects, may influence the Σ masses.[12]

The experimentally found "energy content" of dions (i.e., the energy available in decay) is shown together

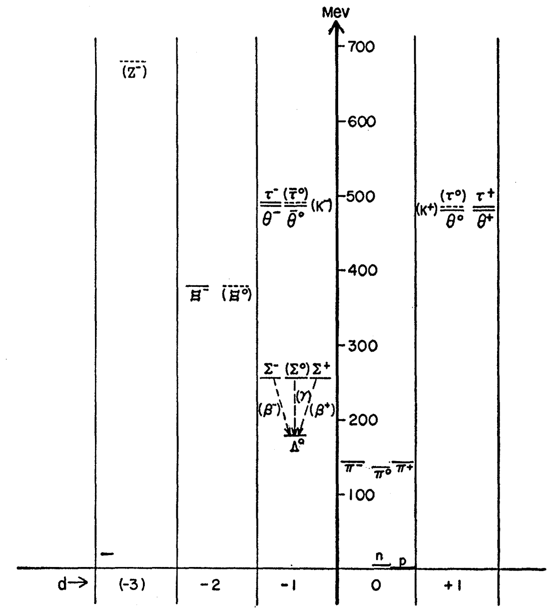

FIG. 1. The energy content (in Mev) of the heavy unstable particles, $d\neq 0$, as well as of the nucleons and pions ($d=0$) is shown. The well-established decay modes of the hyperons and heavy mesons (see reference 2) are not explicitly indicated (e.g., $\Lambda^0\rightarrow p+\pi^-$, $\Sigma^-\rightarrow n+\pi^-$, etc.). There is only indirect evidence for the γ-ray transition $\Sigma^0\rightarrow\Lambda^0$ [see Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **98**, 121 (1953) and W. D. Walker, Phys. Rev. **98**, 1407 (1955)]. On the ideas here presented, the decay $\Sigma^\pm\rightarrow\Lambda^0+e^\pm+\nu$ should be governed by ordinary nucleon β-decay rates, leading to a fraction of $\sim 10^{-4}$ of their π modes of decay.—The τ and θ mesons have approximately equal masses, but are probably different particles; the other K-particles which have been established ($K_{\mu 2}$, $K_{\mu 3}$, K_{e3}) may represent alternate decay modes of τ or θ or both (see below, Sec. VI).

with that of pions and nucleons ($d=0$) in Fig. 1. Since hyperons cannot decay below the nucleon barrier, their energy content is considered equivalent to their difference in mass from that of the proton, which is believed to be absolutely stable,[13] and which has therefore zero energy content. On the compound hypothesis, the decay $\Sigma^\pm\rightarrow\Lambda^0+e^\pm+\nu$ should be governed by ordinary nucleon β-decay rates. The fraction of Σ^+ and Σ^- expected to decay in this manner is $\sim 10^{-4}$ (assuming allowed β transitions and a lifetime[2] of $\sim 0.5\times 10^{-10}$ sec for both Σ^+ and Σ^-).

Our assumptions lead automatically to associated production as well as to a charge asymmetry in production thresholds of $\theta^\pm$ mesons. Some of the cases of associated production which have been abserved in nucleon-nucleon or π-nucleon collisions[2] are shown in column (a) of Table I. They all correspond to $\Delta d=0$. Those given in column (b), on the other hand, have not been reported. They would correspond to $\Delta d=\pm 2$.

As θ^- can only be produced together with a free θ^0 or θ^+, its production is energetically unfavored compared with that of θ^0 or θ^+, which can also be produced together with a "bound" $\bar{\theta}$, thus reducing the threshold value

[11] Our "dionic quantum number" d may be identified with Gell-Mann's "strangeness" s or with the negative value of Sachs' "attribute" a, which were suggested while the ideas here presented were still being developed.

[12] Recently, experimental evidence has been obtained which may be tentatively interpreted as indicating a mass difference $M(\Sigma^-)-M(\Sigma^+)\approx 14m_e$ [Chupp, Goldhaber, Goldhaber, and Webb, University of California Radiation Laboratory Report UCRL-3044; also Proceedings of the Pisa Conference 1955 (to be published)].

[13] Reines, Cowan, and Goldhaber, Phys. Rev. **96**, 1157 (1954).

by the large binding energy (~315 Mev for Λ^0, ~235 Mev for the Σ's).

If multiple production of associated pairs of dions were common, events such as $p+p\rightarrow\Sigma^++\Sigma^++2\theta^0$ might have the appearance of an associated production with $\Delta d=-2$, whenever only the charged particles are observed (e.g., in photographic emulsions). The fact that such events have not been reported thus far can be tentatively interpreted as indicating that multiple production of associated pairs is a comparatively rare phenomenon.

It is easily verified that T and T_z are conserved in fast reactions in which $\Delta d=0$, whereas T_z would not be conserved in a reaction with $\Delta d\neq 0$. It is this fact which leads to complete agreement between permitted and nonpermitted reactions on the compound scheme here presented and the Gell-Mann–Pais scheme (scheme II, reference 6). The explicit assumption of T and T_z as good quantum numbers permits in some cases predictions of relative intensities.

If more than one $\bar{\theta}$ is bound to a nucleon, we find for an even number of $\bar{\theta}$'s isotopic spin doublets, quartets, etc. and for an odd number of $\bar{\theta}$'s singlets, triplets, etc. The cascade particle, Ξ^-, which decays into $\Lambda^0+\pi^-$, may thus be assumed to consist of a nucleon and two $\bar{\theta}$'s and to be a member of a $T=\frac{1}{2}$ doublet, or which the other member (Ξ^0) is hitherto undiscovered. A positive cascade particle, if it existed, would belong to a presumably energetically higher $T=\frac{3}{2}$ quartet and might be unstable against prompt π^+ emission. It is interesting to note that the binding energy of two $\bar{\theta}$'s, (~600 Mev) deduced from the observed Q-value of Ξ^-, is approximately twice that of one $\bar{\theta}$(~315 Mev). To a crude first approximation, this would seem reasonable for bosons.

The cascade particle, Ξ^-, could be made in two ways, either (a) in a single step together with two θ's, or (b) in two steps, by formation first of a fast Λ^0 or Σ, which then picks up a second $\bar{\theta}$, making Ξ^-, together with two free θ's, one in each step. This could happen in a single nucleus, or in two separate nuclei. In each of these reactions we have $\Delta d=0$.

It is natural to assume, whenever we have two or more bound $\bar{\theta}$'s, that they decay successively, so that their combined energy content is not available in a single transition (i.e., $\Delta d>1$ is more highly forbidden than $\Delta d=1$).

TABLE I. Associated production.

(a) Observed ($\Delta d=0$)	(b) Not observed ($\Delta d=\pm 2$)
$\Lambda^0+\theta^0$	$\Lambda^0+\Lambda^0$
$\Sigma^++\tau^+$	K^-+K^-
$K^-+\tau^+$	$\Sigma^\pm+\Sigma^\pm$
Σ^++K^+	Σ^-+K^-
Σ^-+K^+	Σ^++K^-
$\Sigma^++\theta^+$	K^++K^+
Λ^0+K_μ	hyp. frag.$+\Sigma^\pm$
$\Xi^-+2\theta^0$	hyp. frag.+hyp. frag.
Z^-+K	
hyp. frag.$+K$	
hyp. frag.$+\tau^+$	

There is a single example, reported by Eisenberg,[14] of an event which may possibly be interpreted as a new hyperon, here designated as Z (zeta), emitting a K^- particle. If its existence should be confirmed, it could not have a value $d=-2$, as its transition to Ξ^- by γ emission would then be expected to be prompt; it might however have $d=-3$ and decay in the following way:

$$Z^-\rightarrow\Lambda^0+K^-(\Delta d=1).$$

As we have pointed out earlier,[1] the lifetimes of hyperons will be governed by the lifetime of the θ mesons, the fundamental decay being that of a θ meson into two π mesons with absorption of one of the π mesons by the nucleon. It is therefore interesting to note that the lifetimes of all known π-emitting hyperons are of the same order (~10^{-10} sec) as that corresponding to the fastest decay channel known for the θ family,[2] that of $\theta^0\rightarrow\pi^++\pi^-$. T selection rules may be responsible for the longer lifetime of a free $\theta^\pm$ for which the $T=0$ decay channel is absent.

IV. INTERACTION OF DIONS IN FLIGHT OR AT REST

A. Interactions in Flight

The interation with nucleons ($\mathfrak{N}$) of positive and negative θ mesons in flight should show some essential differences. Thus,

I a	$\theta^++\mathfrak{N}$	$\rightarrow$	$\theta^+ +\mathfrak{N}$	scattering
b			$\theta^0 +\mathfrak{N}$	charge exchange
II a	$\theta^-+\mathfrak{N}$	$\rightarrow$	$\theta^- +\mathfrak{N}$	scattering
b			$\theta^0 +\mathfrak{N}$	charge exchange
c			$\Lambda^0 +\pi$	capture
d			$\Sigma^{\pm,0}+\pi$	capture.

The K^+-interactions in flight must be either elastic or inelastic with the K^+-meson surviving or changing into a K^0, thus creating stars of total energy less than the initial kinetic energy of the K^+-meson. On the other hand, K^--mesons may remain free or be captured into a bound state with considerable release of energy. The "capture reactions" IIc, d may therefore be preferred. The recent experimental data on K^+-interactions[15] and K^--interactions[16,17] in flight agree with these conclusions. The experiments show a small cross section for K^+-mesons of 30–120 Mev with emulsion nuclei, ~$\frac{1}{3}$ of the geometric cross section, leading to inelastic scattering and probably also to charge exchange;

[14] Y. Eisenberg, Phys. Rev. **96**, 541 (1954).

[15] Chupp, Goldhaber, Goldhaber, Iloff, Lannutti, Pevsner, and Ritson, University of California Radiation Laboratory Report UCRL–3021; also Proceedings of the Pisa Conference 1955 (to be published).

[16] G. Hornbostel and E. O. Salant, Phys. Rev. **98**, 218 (1953).

[17] Goldhaber, Goldhaber, Iloff, Lannutti, Webb, Widgoff, Pevsner, and Ritson, University of California Radiation Laboratory Report UCRL–3039; also Proceedings of the Pisa Conference 1955 (to be published).

capture of K^--mesons of ~80 Mev takes place with an approximately geometric cross section. Studies of the scattering of K^+- and K^--mesons by free protons might prove of importance for the ideas presented here, as they might reveal the different nature of the two interactions, and throw light on the question of the existence of bound states of K^-+p.

B. Reactions of Negative Dions at Rest

Negatively charged dions can cascade at rest into atomic orbits and then interact with nuclei. The fundamental reactions ($\Delta d=0$) should be the "capture reactions" where θ^- is captured from the free state into a bound hyperon state, and the "transfer reactions" where a $\bar{\theta}$ is transferred from one bound state (e.g., Σ^-) to a more strongly bound state (Λ^0 or hyperfragment).[1,18] These reactions are as follows.

I. The capture reactions

1 ($T=0$ or 1): $\theta^-+p\rightarrow\Lambda^0+\pi^0+\sim180$ Mev ($T=1$)

2 $\rightarrow\Sigma^++\pi^-+\sim$ 95 Mev ($T=0$ or 1)

3 $\rightarrow\Sigma^-+\pi^++\sim$ 95 Mev ($T=0$ or 1)

4 $\rightarrow\Sigma^0+\pi^0+\sim100$ Mev ($T=0$)

5 ($T=1$): $\theta^-+n\rightarrow\Lambda^0+\pi^-+\sim175$ Mev ($T=1$)

6 $\rightarrow\Sigma^-+\pi^0+\sim100$ Mev ($T=1$)

7 $\rightarrow\Sigma^0+\pi^-+\sim$ 95 Mev ($T=1$).

In complex nuclei, the π emission can be replaced by nucleon emission. Also, the θ^- may be bound to a recoil nucleus or a light fragment instead of to a single nucleon (see Sec. V: Hypernuclei). Further we have the following.

II. The Transfer Reactions

8 $\Sigma^-+p\rightarrow\Lambda^0+n+\sim85$ Mev

9 $\Xi^-+p\rightarrow2\Lambda^0+\sim23$ Mev.

As the energy released when a Ξ^- is captured by a complex nucleus is not high, one or both Λ^0's may remain bound to the nucleus or parts of it.

The K^--mesons will interact with free protons with equal *a priori* probabilities in $T=0$ states and $T=1$ states. The $T=0$ states cannot lead to Λ^0 emission, only to Σ emission. For complex nuclei it is not clear whether the T selection rules can be applied in the same manner. If they can be, we would expect K^- capture to lead to more Σ^- than Σ^+ production, as Σ^+ can be produced only from protons, but Σ^- from protons as well as neutrons. Charged Σ's are only found in ~10–20% of the K^- captures.[16,17,19] This may be due to the fact that in passing out of the nucleus a $\Sigma^\pm$ can be "dionically neutralized," with considerable release of energy, by capturing a virtual θ from a nucleon, or transferring a $\bar{\theta}$ to a nucleon, thus leaving a bound or free Λ^0. The change from Σ to Λ^0 can also be accomplished through interaction with the virtual π-meson field. The probability for these processes will be the larger the heavier the nucleus. A Σ^+ can be lost only in the neighborhood of a neutron, a Σ^- only in the neighborhood of a proton. A greater percentage of Σ^- than Σ^+ should therefore escape from heavy nuclei, where neutrons are more numerous than protons, and perhaps more concentrated on the surface,[20] which all particles must cross. For these various reasons, one may expect to find more Σ^- than Σ^+ emission when K^--mesons are captured in heavy nuclei.[21] Present experimental data are too meager to test this expectation.

V. HYPERNUCLEI

One way in which hypernuclei can be formed is by an interaction of a pion or nucleon with a complex nucleus, in which a θ meson is emitted and the $\bar{\theta}$ meson stays behind, bound to the recoil nucleus or to a light fragment (excited fragments, discovered by Danysz and Pniewski[22]; see also Powell,[23] Fry *et al.*,[24] European G-Stack results,[25] and Blau[26]).

If we assume T conservation to hold, we find that binding a θ in a nucleus of odd A leads to isotopic spin singlets, triplets, etc. ($T=0$, 1, 2 etc.), whereas in a nucleus of even A it leads to isotopic spin doublets, quartets, etc. ($T=\frac{1}{2}$, $\frac{3}{2}$, etc.). Within one multiplet we should expect the mass to be nearly constant (except for Coulomb corrections). Similar conclusions were obtained by Dalitz[27] from equivalent considerations involving the binding of a Λ^0 ($T=0$) to a nucleus of mass number $A-1$. Because of the close relation between Λ^0 and the Σ-family and their interaction with the pion-field, such an approach, if pursued further, should include for consistency mixed Λ^0 and Σ "hypernuclear" states.

For $A=2$ no hypernuclei are known. They are possibly not stable against break-up into a hyperon and a nucleon.

For $A=3$ we have the possibility of $T=0$, 1, or 2 multiplets. The individual hypernuclei are designated by their electric charge in Table II. The relative energy of the different T multiplets is not known at present. ${}_{\Lambda}H^3$ ($T_z=0$) is well established. It may be a $T=0$ state

[18] After completion of this paper a discussion of some of the points considered in this section came to our attention: Friedlaner, Fujimoto, Keefe, and Menon, Nuovo cimento **2**, 90 (1955).

[19] Fry, Schneps, Snow, and Swami, Phys. Rev. **100**, 1448 (1955).

[20] M. H. Johnson and E. Teller, Phys. Rev. **93**, 357 (1954); **98**, 783 (1955).

[21] Some factors influencing the Σ^+/Σ^- ratio are similar to those which have an effect on the π^+/π^- ratio (e.g., the Coulomb interaction). See R. E. Marshak, *Meson Physics* (McGraw-Hill Book Company, Inc., New York, 1952), Chapt. 3, Secs. 4 and 6; H. A. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson, and Company, Evanston, 1955), Vol. 2, Sec. 48e.

[22] M. Danysz and J. Pniewski, Phil. Mag. **44**, 348 (1953).

[23] F. Powell, Nature **173**, 469 (1954).

[24] Fry, Schneps, and Swami, Phys. Rev. **99**, 1564 (1955).

[25] European G-Stack collaboration experiments; results privately circulated by the Padua Group, and Nature **175**, 97 (1955).

[26] M. Blau (private communication).

[27] R. H. Dalitz, Phys. Rev. **99**, 1475 (1955).

as no certain example of $_{\Lambda}He^3$ is known; if the existence of $_{\Lambda}He^3$ were established we should expect $_{\Lambda}n^3$ to exist, as it has presumably stronger binding due to the absence of Coulomb repulsion. It is probable that the $T=0$ state is the most stable of the different T multiplets because of its higher symmetry. If the $T=2$ multiplet has members which are stable against Σ emission, they may nevertheless not be stable against Λ^0 emission or γ emission to states of lower T, except the $|T_z|=2$ members, from which neither γ emission nor Λ^0 emission is possible. Of these, the $T_z=-2$ member should be expected to be more strongly bound than the $T_z=+2$ member, because of Coulomb effects; but whether one, or both, of these hypernuclei are stable against breakup into a $\Sigma^{\pm}$ remains a question to be decided by experiment.

For $A=4$, the existence of the $T_z=+\frac{1}{2}$ state, $_{\Lambda}He^4$, as well as of the $T_z=-\frac{1}{2}$ state, $_{\Lambda}H^4$, has been established.[25]

Generally speaking, for each hypernucleus of a given T_z which is shown to exist, there should exist at least one multiplet of hypernuclei with $T\geq|T_z|$.

Table III shows the multiplets of lowest T for hypernuclei of odd and even mass number up to $A=10$. For each atomic number Z, there are three hypernuclei of lowest T ($T=0$ or $\frac{1}{2}$) with mass numbers $A=2Z$, $2Z+1$, $2Z+2$. A good many of these hypernuclei have been established[23–26]—$A=2$ being an important exception—though some have not been identified with certainty. No member of a multiplet of $T\geq 1$ has so far been definitely established, though possible examples have been reported.[24] It is tempting to generalize tentatively from the existing data that for light hypernuclei the multiplet of the lowest T is the most stable, just as it is known to be for other systems: the light nuclei, the nucleon-pion system, and the hyperons.

It is an interesting fact that $\bar{\theta}$ is not bound more strongly to several nucleons than it is to a single one (i.e., in the case of the free Λ^0). On the picture here presented, this is only possible if the force between a nucleon and a $\bar{\theta}$ is of considerably shorter range than the internucleon distance ($\sim 10^{-13}$ cm), and probably smaller than the distance for which nucleon-nucleon forces are believed to be repulsive.

If more than one $\bar{\theta}$ meson is bound in a nucleus (equivalent to more than one Λ^0 in a hyperfragment), we should expect higher total decay energies, e.g., for two $\bar{\theta}$ mesons up to about twice the energy released from normal hypernuclei; as the Λ^0's should be expected to decay successively, no one particle should be emitted with an energy in excess of that obtainable from the decay of a single Λ^0. It is possible that some of the results of Fry *et al.*,[24] indicating hyperfragments of anomalously high-energy release, can be explained in this manner. Other possible explanations of these anomalous hyperfragments in terms of a bound θ (not $\bar{\theta}$) have been give.[24,28] On the ideas here presented, the θ interaction with nucleons may be repulsive, or too weakly attractive to lead to θ compounds with complex nuclei.

TABLE II. Hypernuclei for $A=3$.

$T_z\rightarrow$	$T \diagdown T_z$	-2	-1	0	$+1$	$+2$
	2	−	0	+	++	+++
	1		0	+	++	
	2			+		

TABLE III. Table of hypernuclei (multiplets of lowest T).

Odd A $T=0$ ($A=2Z+1$)		Even A $T=\frac{1}{2}$ ($A=2Z+2$, $2Z$)	
$A=3$	$_{\Lambda}H^3$	$A=2$	$_{\Lambda}n^2$, $_{\Lambda}H^2$
$A=5$	$_{\Lambda}He^5$	$A=4$	$_{\Lambda}H^4$, $_{\Lambda}He^4$
$A=7$	$_{\Lambda}Li^7$	$A=6$	$_{\Lambda}He^6$, $_{\Lambda}Li^6$
$A=9$	$_{\Lambda}Be^9$	$A=8$	$_{\Lambda}Li^8$, $_{\Lambda}Be^8$
		$A=10$	$_{\Lambda}Be^{10}$, $_{\Lambda}B^{10}$

VI. HEAVY MESONS

The preceding discussion would be complete if all K particles could be considered as θ mesons. At present it appears that this is not the case. Six different decay modes of charged heavy mesons of approximately equal mass ($\sim 965\ m_e$) are known[2] (τ, τ', $K_{\pi 2}\equiv\theta$, $K_{\mu 2}$, $K_{\mu 3}$, K_{e3}). So far, no definite difference has been established between these K-particles before decay, and it is therefore too early to say how many different particles are responsible for the decay processes found. However, the analysis of the τ^+ decay carried out by Dalitz[29] indicates that the τ^+ meson and θ^+ meson are probably not identical. It is reasonably certain [see Table I, column (2)], that most of the particles with these different decay modes are dions, with $d=+1$ for the particles of positive electric charge. Thus, one might be tempted to assume excited states of the θ-pion system. If the lowest of these states corresponds to a binding energy $\sim m_\pi c^2$ and is sufficiently metastable against γ emission to allow different states to exist for $\sim 10^{-8}$ sec it might account for the existence of more than one K^+-particle (e.g., a state of character $0+$ for θ^+, and of character $0-$ for τ^+, between which single γ-ray emission is forbidden).[30] In the reaction $\pi^- + p \rightarrow \Lambda^0 + \theta^0$, Fowler *et al.*[31] found in the c.m. system a preferentially forward angular distribution of θ^0's and a corresponding preferentially backward distribution of Λ^0's. Cosmic ray production of Λ^0's[32] indicates a similar preferentially backward distribution. We can tentatively interpret these results as due to a high probability of a knock-on type of process, in which, e.g., a π^- meson collides with a

[28] A. Pais and R. Serber, Phys. Rev. **99**, 1554 (1955).
[29] R. H. Dalitz, Phys. Rev. **94**, 1046 (1954).
[30] *Note added in proof.*—See also S. B. Treiman and H. W. Wyld, Jr., Phys. Rev. **99**, 1039 (1955); T. D. Lee and J. Orear, Phys. Rev. (to be published).
[31] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **98**, 121 (1955).
[32] G. T. Reynolds and S. B. Treiman, Phys. Rev. **94**, 207, 797 (1954).

θ^+ from the virtual system $p=p+\theta^-+\theta^+=\Lambda^0+\theta^+$, with absorption of the π^- by the θ^+. This would indicate that there exists indeed a strong θ-π interaction. If bound states of the system $\theta(T=\frac{1}{2})$ and $\pi(T=1)$ exist, they would form isotopic spin doublets $[(\tau^0), \tau^+]$, quartets, etc. It is well to notice that τ^+ then corresponds to a $d=+1$ particle, in agreement with the type of associated production found for it: $\tau^++\Sigma^+$, etc. [see Table I, column (a)]. The near equaltiy of mass of τ^+ and θ^+ still remains, however, a puzzling fact. No evidence for quartet states exists at present; they may not be stable against π emission and promptly revert to the doublets.[33]

Studies of the relative production cross sections[34] of τ^+ and θ^+ might teach more about the relation between these particles. One must remember, however, that their ratio may be different at decay than at production: the transition $\tau^+\rightarrow\theta^++2\gamma$ (if τ is the heavier particle and the characters of τ^+ and θ^+ are $0-$ and $0+$ respectively) as well as the possibility that other K-decay modes may compete with either τ or θ decay, or with both, might influence the ultimate ratio. Also, if the close relation between τ^+ and θ^+ here assumed is correct, the character of a K^+-meson may be readily changed in collisions with nucleons: $\theta^+\rightleftharpoons\tau^+$.

The arguments concerning a different character of the τ and θ meson, on the one hand, and their close relation, on the other hand, would lose in plausibility if no measurable difference between these mesons before decay were found, e.g., in their relative production cross sections in different collisions and at different bombarding energies, in their interactions with nuclei, in their mass or in their lifetime.

VII. DISCUSSION

If the picture of the heavy unstable particles here presented were to prove correct it would imply that a complete theory of nuclear forces should include, besides terms representing the exchange of π mesons, other terms representing the exchange of θ pairs $(\theta+\bar{\theta})$ between nucleons. Whenever an excess of $\bar{\theta}$'s is present around a nucleon, the new entity may be expected to behave in some respects like a compound, especially if the probability of further θ pairs is comparatively small. This probability may be closely related with the probability of multiple production of θ pairs in high-energy collisions. From cosmic-ray data it appears that multiple production of dion pairs is comparatively rare.[35]

While the question of the "reality" of compounds with binding energies as large as those postulated here may not be decided one way or the other by any one experiment, the compound idea is of heuristic value in qualitative discussions of various experiments, some of which may prove feasible in the near future; e.g. the scattering of K^+- and K^--mesons by nucleons might reveal the existence of interaction terms which change sign when K^+-mesons are replaced by K^--mesons, as we have mentioned above. The scattering of fairly slow K^--mesons by protons, and in particular the sign of the scattering length, might show a behavior analogous to the n-p scattering, in which the existence of the deuteron ground state proves of importance.

Other results which might help decide for or against the compound hypothesis of hyperons would be a determination of their spin,[36] which should be equal to $|I_\theta\pm\frac{1}{2}|$, where I_θ is the spin of the θ (or $\bar{\theta}$) meson, if the ground state of each hyperon is an s-state. Though this cannot be taken for granted, it is a plausible assumption.

The near coincidence in mass between τ and θ raises the question which of the two is the more "fundamental" particle, and whether the parities of Λ^0 and Σ relative to nucleons are even or odd. In fact, whatever the ground state parities of the hyperons are, they may have excited states of opposite parities, decaying rapidly by emission of γ rays which are not readily detected by present techniques. The question of the existence of excited states and of higher presumably promptly decaying multiplets which we have mentioned above, remains one of the most important ones from the point of view here presented.

In their compound model of π mesons (where the π meson is pictured as a compound of a nucleon +antinucleon), Fermi and Yang[37] have discussed some of the theoretical difficulties which a compound theory may encounter; they point out, however, that it need not necessarily involve new particles responsible for this binding. The high binding energies which we have invoked here may require strong and conceivably singular potentials. Some examples of such potentials, leading to binding energies comparable to the rest mass of the bound particles have been analyzed by Case.[38] Only further theoretical and experimental investigations can show whether the ideas here presented can be consistently developed, without introducing a new particle responsible for the binding of θ mesons to nucleons.

We wish to thank Professor A. Pais and Dr. J. Weneser for interesting discussions.

[33] Some events have been observed [Fry *et al.* (reference 24) and E. M. Harth and M. M. Block, Bull. Am. Phys. Soc. 30, No. 5, 13 (1955)] which have been tentatively interpreted as indicating the existence of mesons heavier than K-mesons, and decaying into $K+\pi$. If these particles were established they might speak for the possibility of compounds of two θ's with pions.

[34] τ^+ mesons have been produced by 3-Bev protons [Hill, Salant, and M. Widgoff, Phys. Rev. 99, 229 (1955)], and K^+-particles by 2.2-Bev protons, but relative cross sections are not yet known.

[35] G. Cocconi, Phys. Rev. 94, 741 (1954).

[36] Possible methods of measuring the spins of K-mesons and Σ hyperons were recently discussed by T. D. Lee, Phys. Rev. 99, 337 (1955).

[37] E. Fermi and C. N. Yang, Phys. Rev. 76, 1739 (1949).

[38] K. M. Case, Phys. Rev. 80, 797 (1950).