if the pseudovector interaction is involved. However, this difference is a direct consequence of our perturbation approach with weak coupling theory. If an intermediate or strong coupling calculation were made, the important core term which provides the entire contribution to the low energy (π^+, π^-) cross section in the pseudoscalar theory might be damped out[15] and the two coupling schemes would give approximately the same ratio for these cross sections.

C. Measurement of the Differential (π^+, π^0) Cross Section

Detailed experimental data on the shape of the (π^+, π^0) cross section near the upper end of the π^+ spectrum should indicate the type of interaction between mesons and nucleons.

[15] The damping of the pair term arising from one particular class of Feynman diagrams has been shown by Brueckner, Gell-Mann. and Goldberger, Phys. Rev. 90, 476 (1953).

D. Other Possibilities

It is quite possible that a measurement of the differential (π^+, π^-) cross section either as a function of the angle between the emitted mesons or as a function of the energy of the π^- meson may give information on the type of interaction operative.

The author would like to express his sincere appreciation to Dr. S. D. Drell who originally suggested this investigation and who was a constant source of encouragement and stimulation during the couse of the work. Thanks are also due Prof. L. I. Schiff for many helpful suggestions. During the latter stages of this work the writer benefited greatly from many interesting discussions with Dr. D. R. Yennie.

PHYSICAL REVIEW VOLUME 92, NUMBER 5 DECEMBER 1, 1953

A Hypothesis Concerning the Relations among the "New Unstable Particles"*

M. GOLDHABER
Brookhaven National Laboratory, Upton, New York
(Received August 17, 1953)

An attempt is made to systematize the present knowledge of phenomena concerned with the production, absorption, and decay of the "new unstable particles" in terms of only one "new" particle and its "compounds" with nucleons and π mesons.

THE great variety of new particles which cosmic-ray experiments have revealed in the last few years invites attempts to search for some unifying principle. We should like to put forward here a hypothesis which we are not able to work out in its complete form, but which we have found useful in correlating many phenomena. We shall start from some of the general ideas of Nambu, Oneda, Pais, and others[1] on pair production of V particles and make a number of tentative but specific assumptions. We find in this way that the fairly well-established experimental data are consistent with the following scheme which is designed to unify our knowledge of the "new unstable particles" in terms of only one "new" particle.

ASSUMPTIONS

(1) We shall assume that besides the π mesons there exists one other particle, fundamental in nucleon-nucleon interactions, which we shall call here the η meson. We shall assume that this is the particle which has sometimes been called phenomenologically V_2^0 or V_4^0, and which decays into two π mesons:[2]

$$\eta\rightarrow\pi^++\pi^-+210\text{ Mev}.$$

Thus, its mass is $m_\eta=962m_e$. If we take this decay scheme for granted, the η meson is a boson.[3] It further follows that the spin and parity of η are either both even $(0+, 2+, \cdots)$, or both odd $(1-, 3-, \cdots)$.

(2) Following previous considerations,[1] we shall assume that η mesons are created in pairs either through nucleon-nucleon or pion-nucleon collisions. (This assumption seems necessary to reconcile their comparatively long lifetime, of $\sim10^{-10}$ sec, with their comparatively copious production.)

(3) We shall assume that η is a particle of isotopic spin $T=0$. (Reasons for this assumption are given below in 4b.)

(4) We shall assume that η can form "compounds" with either a nucleon or a pion.

(a) We shall assume that the compound of η and a neutron is a V_1^0:

$$V_1^0=n+\eta-W_1^0,$$

and that the compound of η and a proton is a V_1^+:

$$V_1^+=p+\eta-W_1^+,$$

where the binding energy $W_1^0\approx W_1^+\approx310$ Mev is calculated from the energy release found in the decay of the V_1^0 (and V_1^+). The fundamental decay of a

* Under the auspices of the U. S. Atomic Energy Commission.
[1] For references, see A. Pais, Phys. Rev. 86, 663 (1952).
[2] C. C. Butler in *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (Interscience Publishers, Inc., New York, 1952), Chap. 2, pp. 65–123; Thompson, Buskirk, Etter, Karzmark, and Rediker, Phys. Rev. 90, 329 (1953).
[3] R. W. Thompson *et al.* (see reference 2) emphasize that the present experimental evidence does not exclude the possibility of a decay $V_4^0\rightarrow\pi+\mu$.

$V_1^{0,+}$ consists of the decay of

$$\eta \to \pi^+ + \pi^-,$$

with the absorption of one of the π mesons by the nucleon and emission of the other:

$$V_1^0 \to p + \pi^- + Q_1, \quad \text{where} \quad Q_1 = 37 \text{ Mev.}^4$$

Similarly, the decay $V_1^+ \to n + \pi^+ + \sim Q_1$ should be expected, but the only decay reported is $V_1^+ \to p + \pi^0 + \sim Q_1$.[5a] (See also the discussion below.)

(b) We shall assume that the compound of η and a $\pi^\pm$ is a $\tau^\pm$ meson:

$$\tau^\pm = \eta + \pi^\pm - W_2^\pm,$$

where the measured mass $m_\tau = 975 m_e$ leads to a binding energy $W_2^\pm = 130$ Mev. The fundamental decay here again is the decay of the $\eta \to \pi^+ + \pi^-$, leaving a third $\pi^\pm$:

$$\tau^\pm \to \pi^\pm + \pi^+ + \pi^-.$$

If η were assumed to be a $T=1$ particle, in particular if it were the neutral member of the τ family, doubly charged compounds of nucleons might have been expected on our hypothesis—$T=\frac{3}{2}$ as well as $T=\frac{1}{2}$ "particles." For these there is at present no evidence.

CONCLUSIONS AND DISCUSSION

(I) Some Consequences of T Selection Rules

If we assume the validity of T selection rules, we can draw conclusions about various relative decay rates. The T selection rules have been very successfully employed in describing processes involving strong interactions. While there is no evidence for them in weak interactions such as must be involved in a slow decay process, it still may be of interest to consider their consequences.[5b]

From the assumption that η is a $T=0$ particle and the fact that π mesons are $T=1$ particles of spin 0, it would follow that the hitherto unobserved alternative decay mode,

$$\text{(A)} \quad \eta \to \pi^0 + \pi^0,$$

should exist with approximately one-half the rate of the observed decay mode,

$$\text{(B)} \quad \eta \to \pi^+ + \pi^-,$$

if η has an even spin.[6] A decay into two identical bosons would be forbidden for an odd spin. It would further follow that V_1^0 should also have an alternative decay mode $V_1^0 \to n + \pi^0$. (The decay $V_1^+ \to p + \pi^0$ has been mentioned under 4a).[7] The corresponding τ decay would be $\tau^\pm \to \pi^\pm + \pi^0 + \pi^0$, also hitherto unobserved.[8]

(II) Identity of κ, χ, and τ Mesons

Recent results reported at the Cosmic Ray Congress at Bagnères, France,[9] make it appear possible that $\kappa \equiv \chi \equiv \tau$, and that the observed κ, χ, and τ decays are alternative modes of decay of a single type of particle. Of course, a definite identification is difficult, and all that one can say at present is that no distinction has been made between κ, χ, and τ either on the basis of mass, or mode of production, or lifetime. Some of the alternative modes of decay[9] which would have to be postulated to account for the experimental data are:

$$\tau^\pm \xrightarrow{\kappa \text{ mode}} \mu^\pm + \nu + \gamma,$$

$$\tau^\pm \xrightarrow{\chi \text{ mode}} \pi^\pm + \begin{cases} \gamma \\ \pi^0 \end{cases}.$$

These decay processes would be compatible with the hypothesis presented here, though their relative decay rates cannot be calculated without further specifications. The χ mode can only be an alternative to the 3π mode of decay if the τ meson (and, therefore, on our hypothesis probably also the η meson) has a spin ≥ 1.

(III) Stars Produced by τ^--Mesons

The study of τ^- produced stars may show up some of the following possibilities: a proton in a nucleus may absorb a τ^-, the fundamental reaction being

$$p + \tau^- \to n + \eta + Q,$$

where $Q \sim 5.5$ Mev.[10] Such a reaction, if it occurred, would lead to a rather inconspicuous "star." Other possibilities are given by the fundamental reactions:

(a) $p + \tau^- \to V_1^0 + \pi^0 + 180$-Mev energy,

or

(b) $p + \tau^- \to V_1^+ + \pi^- + \sim 175$-Mev energy.

Some of the available energy may be dissipated in the nucleus, particularly if the $\pi^{0,-}$ is absorbed. The typical appearance of a τ^--produced star will depend on the relative probability of the processes leading to $V_1^0 + \pi^0$ or $V_1^{0,+} + \pi^-$ and the kinetic energy carried away by them. The star will therefore not necessarily be more conspicuous than a π^--produced star. The $V_1^{0,+}$ may also stay bound in the residual nucleus, giving a

---

[4] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953); Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **91**, 362 (1953); Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **90**, 1126 (1953).

[5a] York, Leighton, and Bjornerud, Phys. Rev. **90**, 167 (1953). This Q value may be a lower limit (see note added in proof, at end of paper).

[5b] *Note added in proof.*—A very general discussion of selection rules for elementary particle decay has been recently given by L. Michel (private communication).

[6] The ratio 1:2 for the decay rates $A:B$ arises from the fact that when two $T=1$ states are combined to form a $T=0$ state the states $(T_z=1)(T_z=-1)$, $(T_z=-1)(T_z=+1)$, $(T_z=0)(T_z=0)$ occur with equal weights. If η were a $T=1$ particle the decay into two π^0's would be forbidden, since in the resolution of the wave function of a $T=1$ particle into $T=1$ states, the state $(T_z=0) \times (T_z=0)$ appears with zero weight. [See also A. Pais and R. Jost, Phys. Rev. **81**, 871 (1952).]

[7] If a $V_1^{0,+}$ is regarded as a $T=\frac{1}{2}$ particle it would be expected to show the value 2:1 for the ratio of $\pi^{-,+}$ decay: π^0 decay, if T selection rules are applicable.

[8] See forthcoming papers by R. H. Dalitz [private communication (to be published)].

[9] Private communication from R. W. Thompson and M. Schein. A report of the Bagnères Congress is due to be published.

[10] It is well to keep in mind how poorly the small mass difference, $\tau - \eta$, on which the Q value of this reaction depends, is known at present. Also, the available energy must be reduced by the K binding energy of a τ^- if the nuclear capture takes place from a K orbit. This reaction may therefore only play a role for fast τ mesons.

"delayed star,[11] or be emitted in a fragment, giving the recently discovered[12] "connected stars."

If τ^--produced stars were absent, because τ^- mesons were actually not absorbed by nuclei but rather decayed "at rest," i.e., in a K orbit, the co-planarity of the 3 emitted π mesons would, as a rule, be destroyed.

(IV) Thresholds for Production of V_1 Particles and Heavy Mesons

Any of the particles $V_1^{0,+}$, η, and $\tau^\pm$ can be produced in pairs, the threshold being lowest for production of $V_1^{0,+}+V_1^{0,+}$. The next energetically possible pairs with approximately equal thresholds would be $V_1^{0,+}+\eta$ and $V_1^{0,+}+\tau^\pm$, and at still higher energies one would obtain 2η, $\eta+\tau^\pm$, or $2\tau^\pm$. The approximate threshold energies in the center-of-mass system of two colliding nucleons are:

$$V_1^{0,+}+V_1^{0,+}: \sim 355 \text{ Mev}, \qquad 2\eta: \sim 980 \text{ Mev},$$
$$V_1^{0,+}+\eta: \sim 668 \text{ Mev}, \qquad \eta+\tau^\pm: \sim 990 \text{ Mev},$$
$$V_1^{0,+}+\tau^\pm: \sim 675 \text{ Mev}, \qquad 2\tau^\pm: \sim 1000 \text{ Mev}.$$

A π meson colliding with a free nucleon can produce $V_1^{0,+}+\eta$,[13] 2η, $\eta+\tau^\pm$, or $2\tau^\pm$, but not $V_1^{0,+}+V_1^{0,+}$. The energies necessary in the rest system are here lower by $m_\pi = 140$ Mev compared with nucleon-nucleon collisions, as the π-meson mass can be "used up." On the compound idea presented here, some of the above reactions are of the nature of "pick-up" processes, and may show pronounced angular correlations.

(V) Further Particles

Some of the other "particles," for which only a few examples are known in each case, and where the exact nature of the events observed is still under discussion, do not fit, into the scheme discussed here. Among these are:[14]

$$\zeta^\pm \rightarrow \pi^\pm + \pi^0 + \sim 1\text{–}2 \text{ Mev}, \qquad V_3^0 \rightarrow \tau^\pm + \pi^\mp + \sim 60 \text{ Mev},$$

and others, especially a charged V particle, with a Q value higher than that which we have assumed here for a V_1^+. A further difficulty for the scheme presented here is the apparent rarity of $V_1^{0,+}$ pairs as well as the apparently small value observed for the occurrence of V_1^+ relative to V_1^0. It is too early to say to what extent this may be ascribed to experimental difficulties.

(VI) Indirect Evidence for Pair Production of V_1^0 Particles

The existence of nuclear fragments[15] containing a $V_1^{0,+}$ appears to be a strong point in favor of the assumption of $V_1^{0,+}$ production in pairs; if they were produced singly, e.g., with an angular momentum sufficiently high to explain their lifetime in the free state, it would seem difficult to understand their survival inside nuclear matter for times $\gtrsim 10^{-12}$ sec.

A further point in favor of the assumption that $V_1^{0,+}$ production takes place in pairs is the observation by Schein and collaborators[14] of what appear to be slow V_1^0 particles, with energies up to ~ 5 Mev, emitted from carbon bombarded by π^- mesons of 227 ± 15 Mev. The cross section found was $\sim 2\times 10^{-30}$ per nucleon. At their upper limit, the energy of the mesons used is sufficient to produce one free V_1^0 of a few Mev, with the other member of the pair probably remaining bound with a "typical" nuclear binding energy (~ 10 Mev). Here the interaction of the π^- mesons must have taken place with at least two nucleons. If the V_1^0 particles observed had been produced singly, their energies would have ranged up to ~ 180 Mev.

A tendency for one $V_1^{0,+}$ to stay behind in the residual nucleus might explain in part why V_1^0 pairs have been so rarely reported. The decay of the bound $V_1^{0,+}$ may lead to emission of a slow π meson from a star from which a V_1^0 has been emitted. Such a process might account for the observation of the simultaneous production of a slow V_1^0 and a slow π^+ meson in a cosmic ray interaction reported by Althaus and Sard.[16]

Without specifying further some of the interactions which we have assumed to exist, quantitative predictions remain necessarily limited. We nevertheless publish the hypothesis in its present rudimentary form in the hope that it may be of some heuristic value.

My thanks for several valuable discussions are due to G. F. Chew, M. L. Goldberger, N. M. Kroll, and J. Weneser.

Note added in proof:—In a report on the Cosmic Ray Congress at Bagnères-de-Bigorre given by C. F. Powell [Nature **172**, 477 (1953)], evidence for a charged particle heavier than a proton and decaying with a $Q \sim 130$ Mev is quoted. Should this particle turn out to be the charged counterpart of the V_1^0 particle, such a surprisingly large "charge dependence" of the Q value might help explain the apparent asymmetry in the relative production rate of V_1^+ and V_1^0.—At the Cosmic Ray Congress the symbol θ^0 was suggested for the particle which we have here called η.

[11] Such a star may, under favorable circumstances, show a "double center," the first center corresponding to the location of the nucleus before absorbing the τ^- meson, the second center corresponding to the location of the recoil nucleus after it has come to rest, at which point the $V_1^{0,+}$ decay takes place. The $V_1^{0,+}$ decay may give rise to comparatively slow mesons (see reference 12). It is of interest that of the four stars induced by particles with a mass $\sim 1000 m_e$ which Lal, Pal, and Peters [private communication; Phys. Rev. **92**, 438 (1953)] have recently observed, two show mesons of an energy of ~ 25 Mev, which it is not unreasonable to expect from the decay of a V_1^0 bound with "nucleonic" forces.—Stars with a double center might also be produced by fast nucleons or mesons which can produce $V_1^{0,+}$ pairs, with one $V_1^{0,+}$ staying in the nucleus.

[12] M. Danysz and J. Pniewski, Phil. Mag. **44**, 348 (1953); Tidman, Davis, Herz, and Tennent, Phil. Mag. **44**, 350 (1953); J. Crussard and D. Morellet, Compt. rend. **236**, 64 (1953).

[13] Evidence which can tentatively be interpreted in this manner has been found by Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953).

[14] See Report of Third Rochester Conference on High Energy Nuclear Physics, 1952 (Interscience Publishers, New York, 1953) and Discussions at Bagnères Congress (to be published).

[15] If the existence of connected stars were explained by the presence inside a nucleus, of some particle other than a V_1^0 (or V_1^+), it would be surprising if that particle were not also found bound to single nucleons, thus giving rise to other kinds of $V^{0,+}$ particles decaying into nucleons, for which there is at present no definite evidence.

[16] E. J. Althaus and R. D. Sard, Phys. Rev. **91**, 373 (1953).