five-component wave function,

$$\Psi=\begin{bmatrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi\\ \psi\end{bmatrix}, \tag{10}$$

we see that Eqs. (8) can be written as

$$i\partial\Psi/\partial t=\mathcal{H}\Psi. \tag{11}$$

Here $\mathcal{H}$ is the $5\times 5$ matrix:

$$\begin{bmatrix} 0 & 0 & 0 & 0 & P_1\\ 0 & 0 & 0 & 0 & P_2\\ 0 & 0 & 0 & 0 & P_3\\ 0 & 0 & 0 & 0 & -i\kappa\\ P_1 & P_2 & P_3 & i\kappa & 0\end{bmatrix}. \tag{12}$$

This is certainly of the form of Eq. (2). $\beta_1$ is obtained by putting $P_1=1$, $P_2=P_3=\kappa=0$ in (12). $\beta_2$, $\beta_3$, and $\beta_4$ are obtained similarly. It may be noted that, as for spin one, these matrices are all Hermitian. Direct computation shows that the condition of Eq. (3) is just Eq. (7).

The only remaining question is whether the $\beta_i$ satisfy all the relations implied by (5). This is rather simple to see since the content of (5) is merely the following: Let $n_\mu$ be a unit four vector. Then

$$(n_\mu\beta_\mu)^3=n_\mu\beta_\mu. \tag{13a}$$

Alternatively, to check the relations (5) we need only check that

$$\mathcal{H}^3=(P_1^2+P_2^2+P_3^2+\kappa^2)\mathcal{H}, \tag{13b}$$

for arbitrary $P_1$, $P_2$, $P_3$, and $\kappa$. Direct computation shows this to be true.

### III. REMARKS

Following Schrödinger, we may define the spin operators by

$$S_i=i\epsilon_{ikl}\beta_k\beta_l, \tag{14}$$

where $\epsilon_{ikl}$ is the alternating symbol and $i$, $k$, $l$ run from 1 to 3. The sum of the squares of these three matrices is diagonal. The number 2 appears along the first three diagonal positions and zeros elsewhere. The subsidiary condition (3) shows that in the rest system only the eigenvalue 0 for the spin appears. The situation is much like that noted by Kemmer[2] in that an apparently nonzero spin appears at relativistic energies.

A similarly peculiar result is obtained on introducing an electromagnetic field. The same treatment as above leads to Eq. (11) again, where now

$$\begin{aligned}\mathcal{H}=eV+\kappa\beta_4+\beta\cdot(\mathbf{P}-e\mathbf{A})+(ie/\kappa)\mathbf{P}\cdot\boldsymbol{\beta}\beta_4,&\\ +(\ )=ie/2\kappa\ \epsilon j\kappa i\mathbf{H}j\beta\kappa\beta_4\beta_i&\end{aligned} \tag{15}$$

where $V$, $\mathbf{A}$, and $\mathbf{EH}$ are the scalar potential, vector potential, electric and magnetic field respectively. The non-Hermitian term in (15) is quite similar to the apparent imaginary electric dipole moment one obtains from the Dirac equation.

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# Classification of the Fundamental Particles*

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The decay and production processes of the pions, $K$-mesons, nucleons, and hyperons are classified in terms of selection rules for an integral quantum number, $a$, called the "attribute," which is assigned a definite value for each particle and assumed to be additive when particles are combined. No attempt is made to relate the attribute to other physical properties of the particles. The scheme suggests relationships between processes which have yet to be observed such as the associated production of a cascade particle with two (positive or neutral) $K$-mesons. When it is combined with the notion of isotopic spin ($I$) conservation, it suggests the existence of several new particles, the $\Sigma^0$ of Gell-Mann and Nishijima, a $\Xi^0$ and a neutral $K$-meson differing in its properties from the $\theta^0$. Results of isotopic spin assignments suggest the rule (odd-even rule) that even-$a$ fermions have half-integral $I$, odd-$a$ fermions have integral $I$, and conversely for the bosons. There are also implications concerning the interactions between various particles: the range of the potential binding the $\Lambda^0$ to a nucleon should be of the order of the $K$-meson Compton wave length.

The classification is extended to include electrons, neutrinos, and muons with the result that their attributes must be half-integral. In order to exclude certain unobserved processes, it is necessary to assume that the neutrino is the source of the weak (Fermi) interaction of fermions, in contrast to the notion of the universal Fermi interaction. The existence of an antineutrino is strongly suggested. The $K_{\mu 3}$ and $K_{e3}$ (considered as one particle) may be interpreted as a boson ($K$) or fermion ($\kappa$). In the former case, the decay schemes $K^\pm\to e^\pm+\nu$, $K^0\to 2\nu$, and $K^0\to\pi+\mu+\nu$ are expected to occur. In the latter case, production of the $\kappa$ through the decay process $K\to\kappa+\nu$ is suggested.

Several unusual new events are classified in Sec. VI in order to illustrate the method. A table of thresholds for production of the various particles is included in an Appendix. No excuse is offered for the nonoccurrence of $\pi-e$ decay.

## I. INTRODUCTION

THE purpose of this note is to introduce a scheme for classifying the fundamental particles in such a way as to correlate their modes of production, their observed decay rates, and the interactions between them. The classification is carried out in terms of a single quantum number called the "attribute" which is not given a specific physical interpretation. This scheme provides a useful way to summarize data, and to predict

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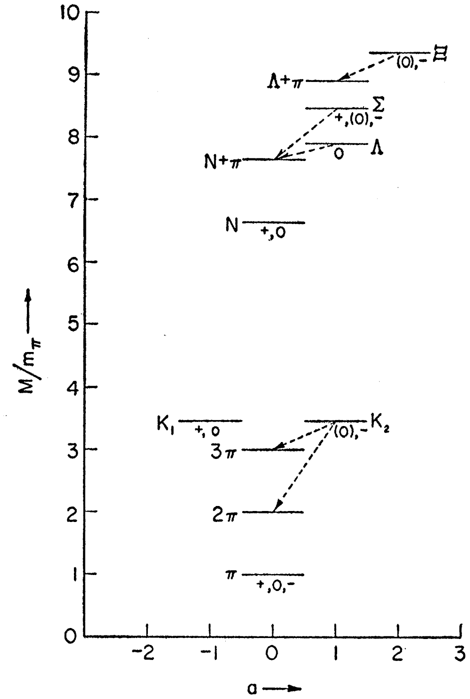

FIG. 1. Classification of the pions, $K$-mesons, nucleons, and hyperons. The vertical scale is mass in units of the pion mass. Electric charges are indicated, those in parenthesis being suggested but not established. Dashed arrows indicate known decay processes.

correlations between phenomena. In this respect the present procedure seems to encompass many features of most proposals[1] that have been set forth to account for the properties of the fundamental particles, although those proposals are generally more specific.

The attribute is assumed to have the following properties:

(1) A definite value of $a$ can be assigned to every fundamental particle.

(2) $a$ is additive, i.e., the value of $a$ for any collection of particles is the algebraic sum of the $a$ values of all the particles.

(3) Transitions having $\Delta a=0$ are very fast.

(4) Transitions having $\Delta a=\pm 1$ are slow, of the order of observed decay rates of fundamental particles.

(5) Transitions having $|\Delta a|>1$ are so slow as to be unobserved.

In addition to these rules and the usual conservation laws, use is made of the conservation of heavy particles, i.e., a heavy particle can be destroyed only by annihilation against a heavy antiparticle. The heavy particles include nucleons and all known hyperons.

## II. CLASSIFICATION OF NUCLEONS, PIONS, K-MESONS, AND HYPERSONS

It is very convenient to present the classification scheme in diagrammatic form by plotting the mass of the particle (or particles) *versus* the attribute, as illustrated in Fig. 1. Then the fast transitions are vertical and the slow transitions connect adjacent columns. A possible assignment of attributes has been made in Fig. 1 for the well-established particles and their decay schemes are indicated by dashed arrows. The nucleon is denoted by $N$($N^+$=proton, $N^0$=neutron) and other particles may be identified by the indicated decay scheme. Each level referring to a single particle is labeled by its observed electric charge states and (parenthetically) by suspected charge states. Arguments for the latter are presented in Sec. III.

The assignments have been made as follows: The pion has been assigned $a=0$ because different numbers of pions appear in so many reactions. Attempts to give it other values have not been successful. The value $a=0$ for the nucleon turns out to be convenient, although not necessary.[2] The advantage is that the collisions between nucleons and between nucleons and pions have a total $a=0$, and hence the sum of the $a$ values of the produced particles must vanish. Since frequent reference must be made to such collisions, we shall refer to them as zero collisions.

It is now required that the $\Lambda^0$ have $a=\pm 1$ in order to account for its slow decay into $N+\pi$. The value has arbitrarily been taken to be $a=1$. The $\Sigma^\pm$ hyperons, those decaying into $N+\pi$ with a $Q$ of about[3] 116 Mev must also have $a=\pm 1$. The value $a=1$ has been chosen in order to be consistent with the choice for the $\Lambda^0$ since they are interrelated by the results on associated production of $K$-mesons, as we shall see below. The cascade particle,[4] $\Xi^-$, decays slowly into $\Lambda^0+\pi$; hence its $a$-value must differ from that of the $\Lambda^0$ by $\pm 1$. The choice $a_\Xi=0$ would lead to spontaneous decay into $N+\pi$; hence we are forced to select $a_\Xi=2$.

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[1] See, for example, D. C. Peaslee, Phys. Rev. **86**, 127 (1952); **91**, 446 (1953); Nuovo cimento **12**, 943 (1954); A. Pais, Physica **19**, 869 (1953); M. Gell-Mann, Phys. Rev. **92**, 833 (1953); M. Goldhaber, Phys. Rev. **92**, 1279 (1953); J. Rayski, Nuovo cimento **12**, 945 (1954); T. Nakano and K. Nishijima, Progr. Theoret. Phys. Japan **10**, 581 (1953); K. Nishijima, Progr. Theoret. Phys. Japan **12**, 107 (1954). The assignment of an attribute according to the rules set forth below would be somewhat indirect in some of these theories. Note that a parity quantum number, such as Pais' $\omega$ parity, may be written as $(-1)^a$ where $a$ is the attribute. When models using compounds of particles are used, as by Goldhaber or Peaslee, all the selection rules follow from an attribute which is assigned to the simple particles. The most direct connection is with the theory of Gell-Mann and Nishijima who propose that the charge $q$ of the particle is related to the $I_3$ component of isotopic spin by

$$q=e(I_3-\tfrac{1}{2}a),$$

and $a$ has just the properties assigned here to the attribute.

[2] An alternative leading to a completely equivalent scheme is to take $a_N=-1$. Then all hyperon $a$-values are reduced by one from the values given in Fig. 1. This is the choice made by Gell-Mann in relating $q$ and $I_3$ (reference 1).

[3] See the report of the Padua Conference, Nuovo cimento **12**, Supplement No. 2, (1954). Also the Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics (Interscience Publishers, Inc., New York, 1955).

[4] E. W. Cowan, Phys. Rev. **94**, 161 (1954). See also the Proceedings of the 1955 Rochester Conference, reference 3.

The $\theta^0$, $\theta^{\pm}$, and $\tau$ mesons must have $a=\pm 1$ because they decay slowly into $a=0$ states, i.e., into either two or three pions. Since $\theta^0$ and a positive meson of about the same mass are observed[5] to be produced in association with the $\Lambda^0$ and $\Sigma^-$, respectively, in zero collisions, these particles must have $a=-1$. We denote them collectively by $K_1$ in Fig. 1. On the other hand, a negative $K$-meson is observed[6] to be captured by nuclei, presumably through either the (fast) reaction

$$K^- + N^{0,+} \rightarrow \Lambda^0 + \pi^{-,0},$$

or the (fast) reactions

$$K^- + N^+ \rightarrow \Sigma^{\pm} + \pi^{\mp},$$
$$K^- + N^0 \rightarrow \Sigma^- + \pi^0.$$

This is forbidden if $a=-1$ for the $K^-$. Hence we are forced to admit another species of $K$-mesons with $a=1$. It is denoted by $K_2$ in the diagram. We shall distinguish between $K_1$-mesons (with $a=-1$) and $K_2$-mesons ($a=1$) in the following since their comparative properties will be under constant scrutiny.

A remark concerning the excited fragments (hyperfragments) may be appropriate here. There is evidence[7] that when the $\Lambda^0$ is trapped in nuclei its lifetime is of the same order as that of the free $\Lambda^0$. This is consistent with the assignment $a_\Lambda=1$ since the interaction with nucleons does not lead to any fast ($\Delta a=0$) process. However neither the $\Sigma$ nor the $\Xi$ can live in the trapped state for an appreciable time since the charge exchange reactions,

$$\Sigma^{+,-} + N^{0,+} \rightarrow \Lambda^0 + N^{+,0}$$

and[8]

$$\Xi^- + N^+ \rightarrow 2\Lambda^0,$$

would be rapid.[9] There is some evidence[8] for hyperfragments of too high a $Q$ to be due to a trapped $\Lambda^0$, and the indicated $Q$ would suggest a trapped $\Sigma$. However, to be consistent with our scheme, it is assumed instead that these excited fragments contain trapped $K_1$-mesons which would be long-lived in nuclear matter.

Note that according to the above reactions, negative hyperons will be captured by nuclei with the formation either of the $\Lambda^0$ or a hyperfragment.

The fact that there is an appreciable binding of the $\Lambda^0$ in nuclei indicates the existence of a strong interaction between the $\Lambda^0$ and nucleon. It may be assumed that the virtual transition

$$\Lambda + N \rightarrow \Lambda + \Lambda' + K_1 \rightarrow N' + \Lambda',$$

i.e., the exchange of a $K_1$-meson, is responsible for this interaction since exchange of a pion is forbidden by the conservation of total isotopic spin. That is clearly consistent with the attribute assignments. The range of the potential generated by this exchange process would be expected to be no greater than the $K$-meson Compton wavelength, that is, about one third of the range of nuclear forces. Then if the interaction has about the same strength as the pion-nucleon interaction, the average binding energy of the $\Lambda^0$ in nuclei should be smaller than that of a nucleon, a result which is consistent with available values of the binding energy.[7]

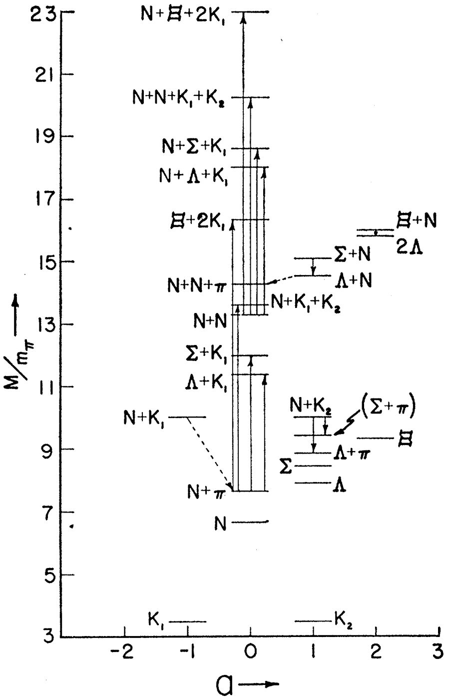

FIG. 2. Extension of Fig. 1 to include various reactions. Solid vertical arrows indicate rapid processes; for production of particles the arrow points upward, for disintegrations, downward. Threshold or $Q$ value (in the c.m. system) is indicated by the length of the arrow.

Processes involving combinations of particles are illustrated in Fig. 2, which is simply an extension of Fig. 1 on a different scale. Production of particles in a collision is indicated by a solid vertical arrow pointing upward. The solid arrow pointing downward indicates spontaneous (fast) decay. The slow transitions, which in this case refer to the excited fragments, are again indicated by broken arrows. Remarks made above concerning production and decay processes are summarized in this figure. Another very important feature of our scheme is also illustrated, namely that in a zero collision the $\Xi$ can be produced only in association with

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[5] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **93**, 861 (1954).

[6] H. De Staebler, Phys. Rev. **95**, 1110 (1954); Naugle, Ney, Freier, and Cheston, Phys. Rev. **96**, 1383 (1954); J. Hornbostel and E. O. Salant, Phys. Rev. **98**, 1202(A) (1955).

[7] M. Danysz and J. Priewski, Phil. Mag. **44**, 348 (1953). References and recent values of the binding energy are given by Fry, Schneps, and Swami, Phys. Rev. **99**, 1561 (1955).

[8] W. F. Fry and M. S. Swami, Phys. Rev. **96**, 809 (1954). Also Fry, Schneps, and Swami, reference 7.

[9] However, W. G. Holladay has pointed out (private communication) that the nuclei consisting of either one or two neutrons plus a $\Sigma^-$ would be stable against the charge exchange process as a consequence of charge conservation.

*two* $K_1$-mesons unless there exists a heretofore unobserved particle having $a=-2$.

## III. CHARGE ASSIGNMENTS

The principle of charge invariance (isotopic spin conservation) of the strong interactions seems well enough established to take it as a basis for further classification of the particles. Therefore we shall attempt to assign a value of isotopic spin, $I$, to each of the particles. In doing so, it will be found *necessary* to follow the suggestion of Nishijima and Gell-Mann[1] that, in spite of first appearances, there need not be a hard and fast correlation between the isotopic spin and the spin angular momentum of a particle. Thus a fermion may have integral $I$ and a boson may have half-integral $I$. However, the "normal" relationship between charge and $I_3$ will be assumed here, $q=eI_3$ for integral isotopic spin and $q=e(I_3\pm\frac{1}{2})$ for half-integral $I$-spin. This makes it possible to predict the existence of hitherto unobserved charge states.

An additional, very common, assumption is made, namely that a charged particle cannot have $I=0$. This rule implies that there must exist a $\Sigma^0$ particle, as suggested by Gell-Mann and Nishijima. The $\Sigma$ may be assigned $I=\frac{1}{2}$, in which case there are two kinds of $\Sigma^0$ particles, one associated with $\Sigma^+$ and the other with $\Sigma^-$, or we may take $I=1$, so that $\Sigma^+$, $\Sigma^0$, and $\Sigma^-$ are the three charge states of the same particle. The latter choice seems the more reasonable since it introduces only one new particle. In either case the $\Sigma^0$ would have $a=1$ and would therefore decay immediately into a $\Lambda^0$, presumably by emitting gamma radiation.[10] The corresponding decay of the $\Sigma^\pm$ is forbidden by charge conservation.

It is expected[11] that every positively charged boson has its negative counterpart, and it is natural to assume that the $K_2^-$ is the counterpart of the $K_1^+$. The assumption that the counterpart of $K_1^+$ is *not* a $K_1^-$ particle is in good accord with the observation[12] that the number of $K^-$ is apparently considerably smaller than the number of $K^+$ produced in the cosmotron. A smaller number is expected if the negative $K$-meson has $a=1$ because in a zero-collision it is produced in association with a $K_1$-meson as shown in Fig. 2. Hence the threshold is higher (see Appendix) than that for production of a $K_1$ in association with a hyperon.

The $K_1^+$ and $K_2^-$ cannot be interpreted as two isotopic spin states of the same particle. That would imply a correlation between $a$ and $I_3$, which is contrary to the principle of charge invariance since $a$ is closely tied in with the strong interactions.[13] We are therefore led to assign $I=\frac{1}{2}$ to each of the $K$-mesons, $K_1$ and $K_2$, in agreement with Nishijima and Gell-Mann.[1] Both charge states of the $K_1$ have been observed but we are led to predict the existence of a neutral $K_2$ which could have the same decay scheme as either the $\theta^0$ or $\tau^0$, but would only be produced in association with a $K_1$ (in a zero-collision).

Since no positive cascade particle seems to have been detected, we are led to assign $I=\frac{1}{2}$ to the $\Xi$ hyperon. Then there should exist a $\Xi^0$ characterized by the scheme

$$\Xi^0\to\Lambda^0+\pi^0,$$

which would not be easily identified.

It is interesting to note that our assignments strongly suggest a correlation between $a$ and $I$ (*not* $I_3$), namely that $I$ is integral for bosons and half-integral for fermions if $a$ is even but $I$ is half-integral for bosons and integral for fermions if $a$ is odd. This rule is suggestive of the Gell-Mann and Nishijima scheme and, up to this point, all of our results are identical with theirs, despite the less restrictive assumptions made at the outset. However, the parallelism does not continue when consideration is given to the fermions of small mass, as will be seen in Sec. IV.

## IV. CLASSIFICATION OF PHOTONS, ELECTRONS, NEUTRINOS, AND MUONS

If the attribute is to be considered as a fundamental property of a particle, it seems that the photon, electron, neutrino, and muon should be assigned an attribute since these may be formed by the decay of particles to which a value of $a$ has been assigned. Hence consideration is now given to the determination of the attribute of each of these particles.

To account for the fast $\pi^0$ decay into photons we are led to assign $a=0$ to the photon. Then the possibility of electron-positron pair production by photons leads to

$$\bar{a}_e=-a_e \tag{1}$$

for electrons, where the bar denotes antiparticle. In the following we shall take $e$ and $\mu$ to be positively charged particles and $\bar{e}$ and $\bar{\mu}$ to be their negative counterparts.

The ordinary beta-decay transitions are written as

$$\begin{aligned} N^+&\to N^0+e+\bar{\nu},\\ N^0&\to N^++\bar{e}+\nu. \end{aligned} \tag{a}$$

If both of these processes are to have the same $|\Delta a|$, Eq. (1) requires that (note that it is found below that $a_e\neq 0$)

$$\bar{a}_\nu=-a_\nu. \tag{2}$$

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[10] Some evidence for the reaction $\pi^-+N^+\to\Sigma^0+\pi^0$ followed by $\Sigma^0\to\Lambda^0+\gamma$ (fast) has been found by W. D. Walker, Phys. Rev. **98**, 1407 (1955), and by Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **98**, 121 (1955).

[11] W. Pauli and V. F. Weisskopf, Helv. Phys. Acta **7**, 709 (1934).

[12] E. O. Salant, report of Brookhaven work at the 1955 Rochester Conference, reference 3.

[13] For example, it might be assumed that $I=1$ and $a\sim I_3$ for the $K$-mesons. Then there would exist a $K^0$ with $a=0$ which could be strongly emitted and absorbed by nucleons although the $K^\pm$ could not. Consequently nuclear forces at short range would not be charge-independent.

Then the decay of a pion may be expressed as

$$\begin{aligned} \pi^+ &\rightarrow \mu + \bar{\nu}, \\ \pi^- &\rightarrow \bar{\mu} + \nu, \end{aligned} \tag{b}$$

and the requirement that these have the same $|\Delta a|$ leads to the condition

$$\bar{a}_\mu = -a_\mu. \tag{3}$$

This result is independent of the order in which neutrinos and antineutrinos have been assigned in reactions (b). The reactions

$$\begin{aligned} \mu + N^0 &\rightarrow N^+ + \nu, \\ \bar{\mu} + N^+ &\rightarrow N^0 + \bar{\nu} \end{aligned}$$

clearly have the same $|\Delta a|$ as (b), hence they need not be considered further.

The processes to be considered in fixing the attributes of the electron, neutrino, and muon are then (a), (b), and

$$\begin{aligned} K_1^+ &\rightarrow \mu + \nu, \\ K_2^- &\rightarrow \bar{\mu} + \bar{\nu}, \end{aligned} \tag{c}$$

and

$$\mu \rightarrow e + \nu + \bar{\nu}. \tag{d}$$

Note here that the neutrino in (c) must be taken to be the antithesis of the neutrino in (b) because the attribute of the *K*-meson is different from that of the pion.

We are immediately faced with the problem of specifying the selection rule on $a$ for these transitions. Since electron, neutrino, and muon processes seem to be governed by a matrix element of the same order as the $|\Delta a| = 1$ transitions between other particles, it would seem reasonable to assume that the relevant coupling is strong but that $\Delta a = \pm 1$ for all such processes. However, it appears to be impossible to arrange the assignments so that this selection rule applies without introducing a contradiction, namely, that at least one of the metastable particles should be extremely short-lived through a $\Delta a = 0$ process.

When we add to this difficulty the fact that no strong process involving these particles has been identified,[14] it seems more reasonable to assume that they are governed by a weak coupling which is accidentally of the correct order to give a matrix element comparable with that of the other transitions. Then we must require that $\Delta a = 0$ for (a), (b), (c), and (d). Under this assumption the attribute values are

$$a_e = a_\nu = a_\mu = -\tfrac{1}{2}. \tag{4}$$

The occurrence of half-integral values of $a$ is a new notion which is a natural consequence of any procedure similar to the one we have followed. It seems to be a result quite inconsistent with Nishijima's and Gell-mann's[1] interpretations of $a$.

Although the assignment (4) takes care of processes (a), (b), (c), and (d), it is necessary to introduce a restriction on the weak coupling responsible for these transitions in order to account for the fact that the reaction

$$\bar{\mu} + N \rightarrow N + \bar{e}$$

is evidently[15] forbidden. Matters may be arranged so as to forbid this process either by a skillful choice of attributes or by making use of the suggestion of Konopinski and Mahmoud[16] that the number of light fermions is subject to a conservation rule. However, both procedures lead to trouble when consideration is given to the $K_{\mu 3}$ and $K_{e3}$ decays. One may identify these as an alternate mode of process (c) such as

$$K_1^+ \rightarrow \mu + \nu + \pi^0,$$

or one may associate them with a different, half-integral spin particle according to a scheme such as

$$\kappa \rightarrow \mu + \nu + \bar{\nu}.$$

In either case, the difficulty is encountered that several new modes of decay are allowed by the scheme, for example,

$$K_1^+ \rightarrow \pi^- + e + \mu,$$

or

$$\kappa^+ \rightarrow \mu^+ + \bar{e} + e.$$

Since events of this kind have not been detected although they should be easily identified, we are compelled to assume tentatively that they are forbidden. The variety of such processes is so large that it is not possible to forbid every one of them by a skillful assignment of attributes even if use is made of the Konopinski-Mahmoud rule.

The only simple way that has been found to prohibit these transitions is to assume that *the weak interaction must involve at least one neutrino*. This implies that the neutrino is the source of the Fermi interaction so that the concept of a really universal Fermi interaction must be abandoned.

Note that the transitions

$$K_1^0 \rightarrow 2\nu,$$

and

$$K_2^0 \rightarrow 2\bar{\nu}$$

are allowed by our rule and are to be expected as alternate modes of decay of the $K_1^0$ and $K_2^0$.

The assignment of attributes cannot lead to an explanation of the very small probability[17] of pion beta

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[14] In this connection it would be very interesting to look for $\mu + \bar{e} \rightarrow \pi^0 + \gamma$ and similar reactions. Note, however, that the muon energy threshold is about 8 Bev in the laboratory system.

[15] Lokanathan, Steinberger, and Wolfe, Phys. Rev. **95**, 624 (1954). W. F. Fry (private communication) also gives the relative probability of $\bar{\mu} + N \rightarrow N + \bar{e}$ as 0.003 compared to the process (c). No systematic attempt to detect $\mu \rightarrow 2e + \bar{e}$ seems to have been made, but it involves the same change of attribute as $\mu + N \rightarrow N + e$ so it should have similar characteristics according to our scheme.

[16] E. J. Konopinski and H. M. Mahmoud, Phys. Rev. **92**, 1045 (1953).

[17] S. Lokanathan and J. Steinberger, Phys. Rev. **98**, 240(A) (1955).

decay, as long as the pion is assumed to have zero attribute. This is a direct consequence of the existence of nucleonic beta decay (no change of attribute of the nucleons). Since the assignment of a nonzero attribute to the pion does not seem tenable, the explanation of this remarkable phenomenon appears to be outside the scope of our considerations here.

### V. REMARKS ON $K$-MESONS

If the $K_{\mu3}$ is to be identified with an alternate mode of decay of the $K_1$-meson or the $K_2$-meson, its decay scheme might be

$$\begin{aligned} &K_1^+\rightarrow\mu+\nu+\pi^0, \\ &K_2^-\rightarrow\bar{\mu}+\bar{\nu}+\pi^0, \end{aligned} \tag{e}$$

according to the selection rules. Recent observation[18] of the three-particle[19] beta decay of a $K$-meson ($K_{e3}$) would then presumably correspond to the processes

$$\begin{aligned} &K_1^+\rightarrow e+\nu+\pi^0, \\ &K_2^-\rightarrow\bar{e}+\bar{\nu}+\pi^0. \end{aligned} \tag{f}$$

This implies that the two-particle mode of decay

$$\begin{aligned} &K_1^+\rightarrow e+\nu, \\ &K_2^-\rightarrow\bar{e}+\bar{\nu} \end{aligned} \tag{g}$$

should compete with the others. It would be most interesting to know whether (g) occurs or not since its absence would provide a strong argument against identifying the $K_{\mu3}$ and $K_{e3}$ with the other $K$-mesons (but the converse argument does not apply).

Another consequence of the identification of the particle as a boson is that the $K^0$ will have an alternate mode of decay:

$$K_1^0\rightarrow\pi^-+\mu+\nu;$$

also,

$$K_2^0\rightarrow\pi^++\bar{\mu}+\bar{\nu}.$$

This may account for the anomalous $V^0$ decays observed[20] by Thompson and his co-workers.

A quite different possibility is that the $K_{\mu3}$ and $K_{e3}$ are manifestations of a different particle (denoted by $\kappa$), a fermion which behaves according to the rules of the particles with half-integral attribute. The decay schemes would be, for example,

$$\kappa\rightarrow\mu+\nu+\bar{\nu} \tag{e$'$}$$

and

$$\kappa\rightarrow e+\nu+\bar{\nu}. \tag{f$'$}$$

Then

$$a_\kappa=-\tfrac{1}{2} \tag{5}$$

and

$$\bar{a}_\kappa=\tfrac{1}{2}. \tag{6}$$

Under this assumption, production of the $\kappa$ cannot take place directly since all of its interactions are weak. The most natural assumption would be that the mass of the $\kappa$ is smaller than that of the $K_1$ or $K_2$ and that it is produced through the modes of decay

$$\begin{aligned} &K_1^+\rightarrow\kappa+\nu, \\ &K_2^-\rightarrow\bar{\kappa}+\bar{\nu}. \end{aligned} \tag{h}$$

The mass measurements on $K$-mesons indicate that the mass difference cannot be much greater than some $40m_e$. Hence this transition would not be detected easily.

If the mass difference were not so small, the interpretation could be excluded on the basis of a remarkable event obtained by the Bristol[21] group. In this event a $K$-meson is produced in a cosmic ray star (which also emits a hyperon) and then proceeds to undergo two strong inelastic collisions before it ends its career as a $K_{\mu3}$ (evidently positive). The $\kappa$ cannot be produced in this manner, nor does it interact strongly enough with nuclear matter to undergo inelastic collisions. However, we may assume that during its peregrinations the $K$-meson was a $K_1$ which decayed into a $\kappa$ after the last collision. The energy of the $K$-meson after the last collision is of the order of 40 Mev; hence the deflection due to neutrino emission would be less than 5°, and might easily go unobserved.

Both the Bristol and Bombay[22] groups have found other events involving inelastic scattering of $K$-mesons which are identified as $\tau$ particles at the ends of their paths. Indications are that at least some of these $K$-mesons are positive. Since the only positive $K$-mesons in our scheme have been taken to be of type $K_1$, the interaction may be due to the virtual transition[23]

$$K_1+N\rightarrow K_1+(\Lambda+K_1')_{\text{virtual}}\rightarrow N'+K_1'. \tag{i}$$

On the other hand, the $K_2$ is capable of strong interaction through the quite different process

$$K_2+N\rightarrow(\Lambda+\pi)_{\text{virtual}}\rightarrow K_2'+N'. \tag{i$'$}$$

The existence of such an interaction is also suggested by the occurrence[8] of excited fragments of high $Q$ which were interpreted as bound $K_1$-mesons in Sec. II. The binding of a $K_1$ implies a rather strong direct coupling between the $K_1$-meson and nucleon, just what is needed to account for the inelastic scattering.

A coupling of this kind would also be expected if the $K_1$ were subject to a strong interaction leading to the virtual transition

$$K_1\rightarrow(K_1+\pi)_{\text{virtual}}, \tag{j}$$

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[18] Friedlander, Keefe, Menon, and van Rossum, Phil. Mag. **45**, 1043 (1954).

[19] See the Proceedings of the 1955 Rochester Conference, reference 3.

[20] Thompson, Buskirk, Etter, Karzmark, and Rediker, Phys. Rev. **90**, 309 (1953); Thompson, Burwell, Huggett, and Karzmark, Phys. Rev. **95**, 1576 (1954).

[21] Reported by W. G. K. Menon at the New York Meeting of the American Physical Society [Phys. Rev. **98**, 1166(A) (1955)]. See also the Proceedings report of the 1955 Rochester Conference, reference 3.

[22] Reported by Yash Pal at the New York meeting of the American Physical Society [Phys. Rev. **98**, 1166(A) (1955)]. See also the Proceedings of the 1955 Rochester Conference, reference 3.

[23] Suggested by R. Serber (private communication).

which is clearly consistent with the selection rule on the attribute. The introduction of (j) suggests that

$$K_2 \to (K_2 + \pi)_{\text{virtual}}$$

too, in which case the interaction between pairs of $K$-mesons would be expected to have the same range as, and probably a strength comparable to nuclear interactions. This should manifest itself through correlations in angle between pairs of $K_1$, $K_2$ mesons produced in association.

## VI. ANALYSIS OF SEVERAL UNUSUAL EVENTS

An unusual event recently noticed by Fry, Schneps, and Swami[24] provides an excellent opportunity to illustrate the method of classification outlined here. They observed that one of the disintegration products of a star produced by a slow secondary particle was a negative $K$-meson. The total visible kinetic energy of the star was 54 Mev. Subsequently, they have found another event in which a $K$-meson of kinetic energy near 40 Mev is the only observed decay product. They suggest that these events may be due either to the nuclear absorption of a new particle or to the decay of an excited fragment in which the particle is bound. The second event might, alternatively, be interpreted as the free decay of the particle. On this basis the particle may be a super hyperon ($Y_s$) or it may be a super $K$-meson ($K_s$).

Let us consider first the possibility that it is a hyperon with the decay scheme

$$Y_s^- \to N^0 + K_2^-.$$

The attribute of $Y_s$ would be $a=0$ or $a=2$. If $a=0$, the disintegration $Y_s \to N+\pi$ would occur rapidly and if $a=2$ the disintegration $Y_s \to \Xi + \pi$ would be rapid. Hence this possibility is excluded. We may consider

$$Y_s^- \to \Lambda^0 + K_2^-,$$

in which case the mass is at least 1425 $m_e$ greater than the nucleon mass. An attribute of $a=3$ is the only possible choice. But then, on nuclear collision the process

$$Y_s^- + N \to \Lambda^0 + \Xi^-$$

would have $\Delta a = 0$, and a $K$-meson would not have been produced in the first event unless the mass of $Y_s$ is so large as to allow

$$Y_s^- + N \to 2\Lambda^0 + K_2^-$$

to occur in competition with the $\Lambda + \Xi$ disintegration, but that has the consequence that the $Y_s^-$ alone is unstable against rapid disintegration into $\Xi + K_2$. It is possible to make the assignment $a=4$ to $Y_s$, but, rather than go to this extreme, we assume that the particle is a super $K$-meson.

The assignment $a=2$ to the super $K$-meson seems to be consistent with both events. The decay scheme would be

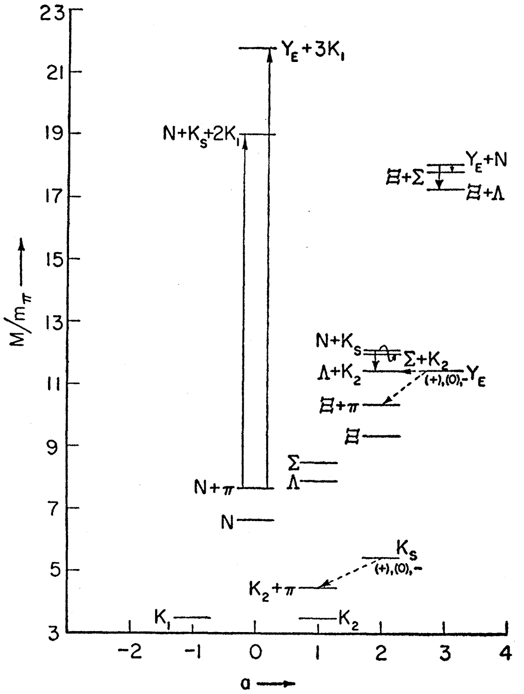

FIG. 3. Suggested properties of the $K_s$ and $Y_E$ particles resulting from the indicated assignments of attribute.

$$K_s \to K_2 + \pi,$$

and the first event (or both events) would be explained as the nuclear capture of $K_s$ leading to the fast reaction

$$K_s + N \to \Lambda^0 + K_2.$$

The mass of the $K_s$ would then lie in the neighborhood of 1500 $m_e$. It is interesting that direct mass measurements[25] on $K$-mesons indicate the existence of a particle with a mass of about this magnitude.

The position of the particle in our scheme is indicated in Fig. 3. Note that, upon its nuclear capture, either a $\Lambda^0$ or a $\Sigma$ (having very low energy) must be formed. Another point of interest is that production in a zero-collision requires the associated production of two $K_1$-mesons, hence the threshold is rather high (see Appendix).

If we follow the even-odd rule suggested at the end of Sec. III, the $K_s$ must be assigned integral isotopic spin, presumably $I=1$. In that case a $K_s^0$ and $K_s^+$ should exist and their decay schemes would be

$$K_s^0 \to K_2^- + \pi^+,$$

or

$$K_s^0 \to K_2^0 + \pi^0,$$

and

$$K_s^+ \to K_2^0 + \pi^+.$$

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[24] Fry, Schneps, and Swami, Phys. Rev. **97**, 1189 (1955).

[25] Daniels, Davies, Mulvey, and Perkins, Phil. Mag. **43**, 753 (1952).

An unusual event having some similar characteristics has been reported by Eisenberg.[26] In this case, the simplest explanation seems to call for a hyperon, $Y_E$, having[27] $a=3$ and the decay scheme

$$Y_E^- \rightarrow \Lambda^0 + K_2^-.$$

Then the mass is 3150 $m_e$. This hyperon would be unstable in nuclear matter through the reactions

$$Y_E + N \rightarrow \begin{cases} \Lambda + \Xi \\ \Sigma + \Xi. \end{cases}$$

It would also have the alternate mode of decay

$$Y_E \rightarrow \Xi + \pi.$$

Production of the $Y_E$ in a zero-collision must take place in association with *three* $K_1$ mesons; hence the threshold is very high (see Appendix). The isotopic spin would be (at least) $I=1$, according to the odd-even rule so the three charge states should occur, as indicated in Fig. 3. Note that $Y_E^+$ could decay only into $\Xi + \pi$ under our assumption that there exists no $K_2^+$-meson.

## VII. CONCLUSION

It has been found possible to conveniently classify most of the available information concerning production and decay of all fundamental particles in terms of a single quantum number, the attribute, satisfying the set of rules set forth in Sec. I. The scheme leads to definite predictions concerning the method of production of the various $K$ particles and hyperons. In particular the thresholds for production in pion-nucleon and nucleon-nucleon collisions are governed by the classification. Threshold energies for these processes are given in the Appendix.

Several general principles seem to emerge from the attempt to fit all particles into the scheme. Most noteworthy are the following:

(1) The odd-even rule; fermions have half-integral isotopic spin when $a$ is even and integral isotopic spin when $a$ is odd. The converse holds for bosons.

(2) The attributes of the weakly interacting light fermions are half-integral.

(3) The Fermi (beta-decay) coupling is a characteristic of the neutrino and in that sense it is not "universal."

(4) The antineutrino must exist (to account for processes (c) and (d) of Sec. IV).

One of the most interesting questions, whether the $K_{\mu 3}$ (and $K_{e3}$) is a boson or fermion may be answered by a search for $K_{e2}$ decays or by establishing the character of anomalous $\theta^0$ events. At present the evidence seems to favor slightly the interpretation of the particle as a boson. A number of other interesting, but so far unheard-of processes are suggested by the scheme, among them associated production of two $K_1$-mesons with either a cascade particle or a 1500 $m_e$ mass $K$-meson and production of three $K_1$-mesons with a super hyperon ($Y_E$); also nuclear capture of negative hyperons with the formation of one or two Λ's, a hyperfragment or possibly a cascade particle.

It remains to be seen whether the $K_s$ and $Y_s$ really exist. Other explanations of the events are possible, but evidently more complicated.

This work was stimulated by discussions with the Wisconsin high-energy group, particularly with W. F. Fry and W. D. Walker. Conversations with G. A. Snow, W. G. Holladay, and many others have been helpful.

## APPENDIX

The threshold energies for the production of $K$-mesons and hyperons are determined by the production scheme, as illustrated in Figs. 2 and 3. These energies have been calculated for the zero-collisions and the results are displayed in Table I. The kinetic energy of the pion or nucleon beam is given in the laboratory system under two conditions, when the target is a nucleon at rest and when the target is a heavier nucleus. In the latter case the kinetic energy of the target nucleon in the nucleus has been taken to be 25 Mev and the direction of motion opposite to that of the incident beam.

TABLE I. Threshold energies in Bev.

| Produced particle | Pion-nucleon | Pion-nucleus | Nucleon-nucleon | Nucleon-nucleus |
|---|---|---|---|---|
| $K_1$ | 0.75 | 0.59 | 1.57 | 1.11 |
| $K_2$ | 1.34 | 1.08 | 2.48 | 1.82 |
| ($K_s$) | 3.22 | 2.69 | 5.16 | 3.94 |
| $\Lambda^0$ | 0.75 | 0.59 | 1.57 | 1.11 |
| $\Sigma$ | 0.90 | 0.69 | 1.80 | 1.31 |
| $\Xi$ | 2.25 | 1.73 | 3.75 | 2.86 |
| ($Y_E$) | 4.74 | 3.76 | 7.20 | 5.60 |

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

[27] The possibility $a=2$ with the decay scheme $Y_E^- \rightarrow N + K_2^-$ and mass 2805 $m_e$ is excluded because such a particle would decay immediately into $\Xi + \gamma$.