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Charge Independence Theory of V Particles*

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Based on the charge independence hypothesis the properties of V particles are theoretically investigated. It is found that the curious behaviours of these unstable particles are most simply interpreted in terms of the η-charge conservation law which directly results from the C.I. hypothesis and suitable isotopic spin assignments to these particles. The topics which are discussed in this paper are

(a) the isotopic spin assignments to V particles,
(b) the concept of the η-charge,
(c) the η-charge conservation law which is to incorporate with the even-odd rule, the so-called "cascade" decay of some hyperons, and the positive excess of long-lived K particles,
(d) the interpretation of heavy nuclear fragments,
(e) the possible models of τ-mesons.

§ 1. Introduction

Ever since the first observation by Rochester and Butler, so much information on hyperons and heavy mesons has been accumulated that some of the many puzzling questions on these curious particles are being resolved. We are sometimes motivated to seek for an ordering principle by which species of new particles can be described in a unified manner. It is expected that the solution of this problem would serve as a clue to remove the difficulties inherent in the present field theory.

Besides such problems of rather general nature, we are interested in speculating possible models of these unstable particles that can consistently account for their various properties together with their implications to the pion-nucleon interaction.

In this paper, we shall investigate the latter problems. The theory of V particles is closely related to the *pi*-meson theory on which we base our arguments, and through the present work it will become clear that these particles are so strongly coupled to each other that we cannot treat them separately for quantitative calculations.

Hence the theory of these strongly coupled particles is sharply contrasted to the quantum electrodynamics which is practically a closed theory. As the quantitative theory of pion-nucleon interactions is not yet fully successful in explaining the experimental material, we cannot expect any quantitative theory of V particles at present. We shall rather discuss them qualitatively by making use of general invariance principles in quantum field theory but not referring to the details of the theory. Especially the principle of charge independence is found to play the most important rôle in understanding the characteristic features of these particles.

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* Preliminary reports of the present paper have been published in this journal. See references 1) and2).

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After such qualitative investigations we shall examine by assuming a specific model, whether or not the experimentally available data are consistent with each other. Preliminary calculations show that we can consistently account for (a) the cross section of the elementary process

$$\pi^- + p \rightarrow \Lambda^0 + \theta^0,$$

established by the Cosmotron experiments and (b) the binding energy of the Λ^0 particle in the heavy nuclear fragment ${}^+H_1^3$ which is known to decay as

$${}^+H_1^3 \rightarrow He_2^3 + \pi^-,$$

by assuming the presence of an interaction of the type $\Lambda N\theta$.

By exploiting the magnitude of the coupling constant for the interaction $\Lambda N\theta$ estimated above one can infer how much modification results in the pion-nucleon interaction caused by the presence of the V particles. For instance, according to a tentative calculation, about 10% of the anomalous magnetic moment of a proton is supplied by V particles.

Although the influences of these particles are subject to fluctuations from case to case, we may conclude that one cannot ignore the presence of these particles for quantitative investigations of pion-nucleon interactions.

§ 2. Brief summary of the experimental evidences[3)]

Before working with the theory of V particles, it will be instructive to briefly summarize the experimental evidences upon which our reasoning stands.

(1) *Hyperons*

Of the various new particles the best known one is the Λ^0 particle which decays as

$$\Lambda^0 \rightarrow p + \pi^- + Q, \quad Q \sim 37 \text{ Mev.} \quad (m_{\Lambda^0} \sim 2182\, m_e) \tag{2·1}$$

with the mean lifetime of about 3×10^{-10} sec.

The most characteristic features of the Λ^0 particle as well as other V particles are their large abundances and long lives. It had been the central problem in the theory of V particles how to reconcile these two contradictory features with one another.

Later on evidences for the existence of charged hyperons were presented. Their modes of decay may be represented by

$$\Lambda^+ \rightarrow p + \pi^0, \ \Lambda^\pm \rightarrow n + \pi^\pm, \quad Q \sim 130 \text{ Mev.} \quad (m_{\Lambda^\pm} \sim 2370\, m_e) \tag{2·2}$$

These charged hyperons are heavier but less abundant than Λ^0.

Besides, there are evidences for the "cascade" decay of negatively charged hyperons;

$$Y^- \rightarrow \Lambda^0 + \pi^-, \ (\Lambda^0 \rightarrow p + \pi^-). \quad (m_Y \sim 2800\, m_e) \tag{2·3}$$

(2) *Heavy mesons*

It is now established by cloud chamber experiments that there exists a neutral heavy meson, the θ^0-meson, which decays as

$$\theta^0 \rightarrow \pi^+ + \pi^- + Q, \quad Q \sim 214 \text{ Mev.} \quad (m_\theta \sim 966\, m_e) \tag{2·4}$$

There are various kinds of charged heavy mesons with the common name of K particles. They are further specified according to their modes of decay:

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$$\tau^{\pm}\to\pi^{\pm}+\pi^{+}+\pi^{-} \text{ or } \tau^{\pm}\to\pi^{\pm}+2\pi^{0}, \quad (m_{\tau}\sim 966\, m_e) \tag{2·5}$$

$$\kappa\to\mu+?^{0}+?^{0}, \tag{2·6}$$

$$\chi\to\pi+?^{0}, \quad (900-1000\, m_e) \tag{2·7}$$

$$K_{\mu}\to\mu+?^{0}, \quad (912\pm 20\, m_e) \tag{2·8}$$

etc.

There might be alternative modes of decay of an identical particle or conversely different particles with the same name. If different names correspond to the alternative modes of decay of the same particle, their branching ratio should be the same under any experimental condition.

However, there seem to be at least two kinds of heavy mesons.

(a) It is reported that comparatively long lived S particles ($\sim 10^{-8}$ sec) or some of the K particles observed in photographic emulsion exhibit a large preponderance of positive ones over negative.

(b) On the other hand, positive and negative V particles are observed with equal frequency in cloud chambers.

In order to reconcile the above two kinds of events with one another we tentatively assume that they belong to different kinds. Discussions in this paper are limited to the former which, as we shall see later, is considered to be closely related to the θ^{0}-meson.

(3) *Heavy nuclear fragments*

After the discovery by Danysz and Pniewski[4] several examples of the so-called heavy nuclear fragment have been reported. These phenomena are reasonably interpreted to represent the spontaneous decays of light nuclei emitted from nuclear disintegrations. Because of their long lifetimes compared to their large Q-values it is assumed that a nucleon is substituted by a Λ^{0} particle in the heavy nuclear fragment.

Bonetti and others[5] observed an interesting example

$$^{+}H_1^{3}\to He_2^{3}+\pi^{-}+Q, \quad Q=41.7\pm 1 \text{ Mev.} \tag{2·9}$$

from which the binding energy of the Λ^{0} particle in $^{+}H_1^{3}$ was deduced to be about 1.5 Mev.

Hill and others[6] found another example

$$^{+}He_2^{4}\to He_2^{3}+p+\pi^{-}. \tag{2·10}$$

The binding energy of the Λ^{0} in this case was estimated to be about 4 Mev. As we shall see later, these values are useful in estimating the magnitude of strength of the nuclear interaction of the Λ^{0} particle.

Further, Debenedetti and others[7] found a very interesting star in which a τ-meson and a heavy nuclear fragment $^{+}H_1^{3}$ were emitted simultaneously. This example serves as a support for the hypothesis that a Λ^{0} particle is loosely bound in a heavy nuclear fragment in view of the pair production of heavy unstable particles.

(4) *Elementary processes*

The information on elementary processes is very instructive in studying the nature of V particles. The production process that has first been established from the Cosmotron experiment[8] is

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$$\pi^- + p \to \Lambda^0 + \theta^0, \quad (\sigma \sim 1 \text{ mb}), \qquad (2\cdot11)$$
$$\text{energy of } \pi^- = 1.5 \text{ Gev}$$

The long standing contradiction between the relatively copious production of V particles and their long lifetimes is resolved by this observation of the pair production of V particles. The branching ratio of the above process to the total one is given by

$$\sigma(\pi^- + p \to \Lambda^0 + \theta^0)/\sigma(\pi^- + p, \text{ total}) \sim 1/40 . \qquad (2\cdot12)$$

It is worth while to notice in the Cosmotron experiments that no particle has been produced so far in nucleon-nucleon collisions,[9] whereas the production has been found in nucleon-nucleus collisions.[10]

With a multiplate cloud chamber, De Staebler[11] observed such reactions that were interpreted as

$$K^- + n \to \Lambda^0 + \pi^-,$$
$$K^- + p \to \Lambda^0 + \pi^0. \qquad (2\cdot13)$$

These processes are the reciprocals of the reaction (2·11).

In the following sections, we show that some of the above experimental evidences as well as other data can consistently be accounted for.

§ 3. Charge independence hypothesis for V particles

The central problem in the theory of V particles had been how to reconcile the relatively copious production of V particles with their long lifetimes as measured on a nuclear time-scale. The theoretical solution of this problem has been the hypothesis of pair production of heavy unstable particles,[12)-14)] and indeed it was experimentally proved as described in the previous section. Since then, this hypothesis has widely been accepted. As this hypothesis is purely phenomenological in nature, however, various attempts to relate it to the intrinsic properties of quantum field theory have been proposed.[15)-17)] In this paper we shall prove this hypothesis theoretically on the basis of the charge independence. We shall briefly summarize what will be necessary for this purpose.

From the investigations on the levels of isobaric nuclei, nuclear reactions, and the nuclear interaction of pions it is now established that the principle of charge independence (abbreviated as C.I. hereafter) is valid for the pion-nucleon interaction and nuclear forces at low energies of the order of 10^2 Mev.

We classify all elementary interactions into three categories according to their orders of the strength.

(a) *Charge independent interactions*

The strongest interactions of the three groups are the charge independent ones for which the isotopic spin I is conserved. As is well known, the pion-nucleon interaction belongs to this class. There cannot be any interaction that is as strong as the pion-nucleon interaction but is not charge independent, otherwise one could not recognize the C.I. principle for the pion-nucleon interaction.

From the cross-section of the process (2·11) and the binding energies of the Λ^0

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particle in the heavy nuclear fragments, the nuclear interaction of the Λ^0 particle is inferred to be much stronger than the electro-magnetic interaction. Hence we are allowed to take it for granted that the nuclear interaction of the Λ^0 particle is charge independent.

However, it is still an open question whether the nuclear interaction of other kinds of V particles are also charge independent. In the present paper, we tentatively assume that the nuclear interactions of all kinds of V particles belong to this category.

Charge independent interactions are inevitably charge symmetric.

(b) *Electromagnetic interactions*

The principle of C.I. is not strict but approximate, otherwise the charge multiplets, such as the positive, neutral and negative pions, could not be distinguished so that the principle itself would not be called under such a name. As far as we know, slight deviations from the C.I. can be attributed to the electromagnetic interaction and small mass differences among charge multiplets. Hence we may regard the electromagnetic interaction as the strongest one among those that violate the C.I. For the electromagnetic interaction the total isotopic spin is not conserved, but its third component I_3 is still conserved.

(c) *Very weak interactions*

As is clear from the above classification, interactions other than the above two groups should be weaker than them.

In general, neither the total isotopic spin I nor its third component I_3 is conserved for such interactions. The interactions responsible for various observable decay processes and Fermi interactions belong to this third group.

What is interesting is the fact that the interactions in this category are much weaker than the first group by about twelve orders. We do not know yet the reason why there is so large a gap, but it might be due to the experimental difficulties in detecting the interactions of intermediate strength if there were any,[18] since they would lead to too small cross-sections for production or scattering processes on one hand, and too short lifetimes for decay processes on the other hand. Or, one might suppose that the large gap is real since there seem to be regularities in the strength of the interactions between Fermion-Fermion (universal Fermi interactions) and Boson-Fermion (universal weak Boson-Fermion interactions).[19] In this paper we stand on the latter point of view.

Based on the above assumption concerning the classification of the elementary interactions and the experimental evidences described in § 2, we shall assign the isotopic spins of V particles.

(1) *Hyperons*

In assuming the isotopic spin of Λ^0, the problem is whether or not there is a charged counter particle to Λ^0. If it were to exist, its mass should approximately be equal to that of Λ^0 and it would have to be produced as many as Λ^0.

Experimentally charged hyperons $\Lambda^{\pm}$ are known, but their masses are considerably heavier than the Λ^0 mass and are less copiously produced than Λ^0. These facts lead us to conclude that these charged hyperons cannot be the counter particles to Λ^0. Hence we assign the isotopic spin of Λ^0 as

$$I=0 \quad \text{for} \quad \Lambda^0. \tag{3·1}$$

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It may be natural to assume that Λ^+ and Λ^- belong to the same charge multiplet. A number of reasons make us assign

$$I=1 \tag{3·2}$$

to $\Lambda^\pm$ together with a supplementary neutral particle. This neutral particle is different from the former Λ^0 and they are distinguished by subscripts indicating their isotopic spins as

$$\Lambda_0^0, \tag{3·1′}$$

$$\Lambda_1^+,\ \Lambda_1^0,\ \Lambda_1^-. \tag{3·2′}$$

The Λ_1^0 particle is not experimentally observed, since it is supposed to undergo a radiative decay with quite a short lifetime:

$$\Lambda_1^0 \to \Lambda_0^0 + \gamma\,. \tag{3·3}$$

It must be noticed that the decay of Λ_1 through

$$\Lambda_1 \to \Lambda_0 + \pi \tag{3·4}$$

is energetically forbidden.

Discussions on the charged hyperon Y^- which exhibits a cascade decay are made later.

(2) *Heavy mesons*

From the Cosmotron experiments, the process

$$\pi^- + p \to \Lambda_0^0 + \theta^0 \tag{2·11}$$

is established. The cross-section of the above process amounts to about 1/40 of the total cross-section at 1.5 Gev. On the other hand, the ratio of the elastic scattering $\pi^- + p \to p + \pi^-$ to the total[20] at the same energy is known to be about 16/90, so that we have

$$\sigma(\pi^- + p \to \Lambda_0^0 + \theta^0)/\sigma(\pi^- + p \to p + \pi^-) \sim 1/7\,.* \tag{3·5}$$

From the above relatively large ratio and the classification of the elementary interactions discussed before, it is reasonable to assume that the isotopic spin is conserved for the process (2·11).

Hence the isotopic spin of θ^0–meson should be either 1/2 or 3/2 as seen from

$$\begin{array}{lll} & \pi^- + p \to \Lambda_0^0 + \theta^0 & \\ I & 1,\ 1/2 & 0,\ 1/2 \text{ or } 3/2 \\ I_3 & -1,\ 1/2 & 0,\ -1/2\,. \end{array} \tag{3·6}$$

The latter choice results in the existence of a doubly charged heavy meson of the comparable abundance with θ^0, which is excluded experimentally.

Hence we have

$$I=1/2 \quad \text{for } \theta^+ \text{ and } \theta^0. \tag{3·7}$$

The charged counter particle to θ^0 should be positive since $I_3=-1/2$ for θ^0. In this

* A recent observation by Eisberg et al. has led them to the conclusion that only 1/4 of elastic events are interpreted as the reaction scattering, while the rest of them are due to the diffraction scattering. If this interpretation is granted, 1/7 in (3·5) should be revised as 1/5. Then the coupling constant estimated in § 5 should be increased correspondingly.

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paper, we shall denote the θ–mesons as Π (or more specifically Π_1), but the Π–meson is called θ only when it undergoes the characteristic two pion decay $\Pi \to \pi + \pi$.

As we shall see later, the Π^0–meson, being a member of a charge doublet, should be distinguished from its charge conjugate particle $\tilde{\Pi}^0$, and $\tilde{\Pi}^0$ and $\tilde{\Pi}^-$ form another charge doublet.

$\tilde{\Pi}^-$ is the charge conjugate particle of Π^+ and its existence seems to be supported by the process (2·13), since they can be interpreted as

$$\begin{aligned} &\tilde{\Pi}^- + p \to \Lambda_0^0 + \pi^0, \\ &\tilde{\Pi}^- + n \to \Lambda_0^0 + \pi^-. \end{aligned} \tag{3·8}$$

§ 4. Qualitative discussions[1),2)]

In this section we shall discuss the nature of V particles qualitatively on the basis of the isotopic spin assignments in the previous section.

(I) The particles Λ and Π cannot be composed of nucleons and pions. Since both the ordinary and isotopic spins are half-integral for a nucleon and integral for a pion, both spins of a system composed of them should be either integral or half-integral. However, it is not the case for these particles and this is a reason against the composite theory of V particles. For the time being, we shall assume them as elementary.

Alternatively we can assume Λ to be composed of a nucleon and a Π–meson[21)] without violating the C.I. principle. However, this assumption requires so large a binding energy of Λ as $B = m_N + m_\theta - m_\Lambda \sim 300$ Mev. and hence a very strong nuclear interaction of Π–meson in contradiction to our experience.

(II) The Π^0–meson is described by a complex wave function[1),16)] so that it must be distinguished from its charge conjugate particle $\tilde{\Pi}^0$.

Since Π^+ and Π^0 form a charge doublet, their transformation properties in isotopic space are identical with those of proton and neutron, *i.e.* the wave function of the Π–meson is a spinor in isotopic space. Hence Π^0 as well as Π^+ should be described by complex wave functions, and Π^0 must be distinguished from its charge conjugate particle $\tilde{\Pi}^0$ in contrast with other neutral Bosons such as a neutral pion and a photon.

In the case of a pion, there are three charge states, positive, neutral and negative, forming a charge triplet ($I=1$), and under rotations in isotopic space the three bases

$$\pi^+,\ \pi^0,\ \pi^-$$

are mutually transformed irreducibly. Furthermore, there are representations in which π^0 can be described by a real wave function so that the charge conjugate particle of π^0 is π^0 itself.

In the case of Π–meson, on the contrary, two sets of bases

$$\Pi^+,\ \Pi^0 \quad \text{and} \quad \tilde{\Pi}^-,\ \tilde{\Pi}^0$$

are not mixed under rotations, *i.e.* they form separately irreducible sets of bases. These two sets are transformed into each other only through the operation of charge conjugation.

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These relations would schematically be understood in Fig. 1.

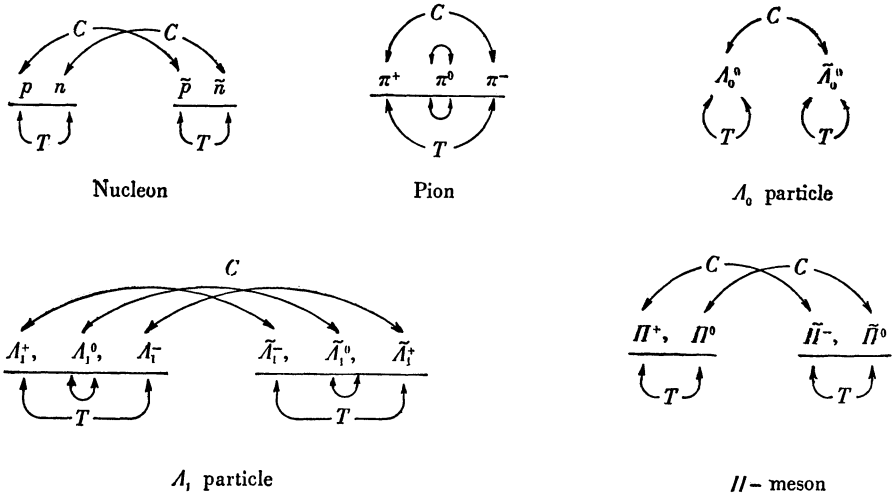

Fig. 1

In the above Fig. 1, the underlines combine bases which are mutually transformable under rotations in isotopic space, and C and T represent the operations of charge conjugation and charge symmetry, respectively. The charge symmetry operation T is defined as the rotation of 180° around the " 1 " axis in isotopic space.

Introduction of the η-charge

In developing the C.I. theory of V particles, the concept of η—charge is most useful. As is well known there is always an intimate relationship between the third component of the isotopic spin I_3 and charge q for each elementary particle which has a definite isotopic spin, *e.g.* $q=I_3+1/2$ for nucleon and $q=I_3$ for pion.

In general we may write

$$q=I_3+1/2+(1/2)\eta_a \qquad (4\cdot 1a)$$

for a baryon* N_a, and

$$q=I_3+(1/2)\eta_b \qquad (4\cdot 1b)$$

for a heavy meson Π_b.

From the definition, the η-charge of nucleon or pion is zero. For Λ and Π, we have

$$\eta(\Lambda_0)=\eta(\Lambda_1)=-1\,,$$
$$\eta(\Pi)=1\,. \qquad (4\cdot 2)$$

An anti-particle, *i.e.* charge conjugate particle, has an opposite η-charge of the particle as is the case for the electric charge,** and we have

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* A baryon is a hyperon which is a member of the nucleon family.

** For an anti-baryon $\tilde{N}_a$, we have

$$q=I_3-\frac{1}{2}+\frac{1}{2}\eta_a',\quad \eta_a'=\eta(\tilde{N}_a),$$

instead of (4·1a).

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$$\eta C=-C\eta\,,\quad qC=-Cq\,, \tag{4·3}$$

where C is the operation of charge conjugation.

Let us consider a system of particles with definite isotopic spins. Then the total charge q of this system is expressed in reference to (4·1a) and (4·1b) by

$$q=I_3+1/2\cdot\sum_a n(N_a)+1/2\cdot\sum_a \eta_a n(N_a)+1/2\cdot\sum_b \eta_b n(\Pi_b), \tag{4·4}$$

where n is the number of particles minus the number of anti-particles. By putting

$$b=\sum_a n(N_a),\quad \eta=\sum_a \eta_a n(N_a)+\sum_b \eta_b n(\Pi_b), \tag{4·5}$$

we have

$$q=I_3+b/2+\eta/2\,. \tag{4·6}$$

From the stability of matter, it is known that b, the number of baryons, is a strict quantum number.

For production and scattering processes in which only charge independent and electromagnetic interactions are effectively operating, q and I_3 are conserved. In this case q is the total charge of particles with strong nuclear interactions but does not involve the charge of other particles like μ-mesons or electrons.

From the conservation laws of q, I_3 and b and the eq. (4·6), follows the conservation theorem of the η-charge.

(III) The η-charge is conserved for processes caused by charge independent and electromagnetic interactions.[2)]

Utilizing this conservation law, we can account for various properties of V particles as we shall see in what follows.

(IV) The even-odd rule[14)] is a direct consequence of the η-charge conservation law. Let the group of elementary particles with η-charge $\pm s$ be G_s, then elementary particles with strong nuclear interactions are divided into several groups

$$G_0,\ G_1,\ G_2\cdots\cdots\,. \tag{4·7}$$

The pion and nucleon belong to G_0, and Λ_0, Λ_1 and Π to G_1. Since there is no evidence for the existence of other charge states of the hyperon Y^- which undergoes the cascade decay, we may assume

$$I=1/2 \text{ for } Y^0 \text{ and } Y^-,\ \text{or } I=0 \text{ for } Y^-. \tag{4·8}$$

In the above cases the η-charge of Y is given, respectively, by

$$\eta(Y)=-2\,,\quad \text{or}\quad \eta(Y)=-3\,,$$

and Y belongs to G_2 or G_3.

Let us consider a strong interaction of the form

$$N_i N_j \Pi_k \tag{4·9}*$$

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* In a previous paper,[18)] we have similarly divided the elementary particles into several groups in order to generalize the even-odd rule so as to include the interpretation of the so-called cascade decay. Although this theory is completely phenomenological, it is a special case of the present scheme with more specified interactions of the types, $N_0 N_0 \Pi_0$, $N_i N_0 \Pi_i$, $N_i N_i \Pi_0$.

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for which the η-charge is conserved. N_i denotes the baryon of the group G_i and Π_k the heavy meson of the group G_k. Then the conservation of η-charge requires

$$i+j+k=\text{even} \tag{4·10}$$

as a necessary condition. Conversely, interactions of

$$i+j+k=\text{odd} \tag{4·11}$$

should be very weak since they violate the conservation law. We shall call these interactions even and odd respectively.

With (4·10) and (4·11) the copious production of V particles is reconciled with their striking stability.

Processes allowed by the even-odd rule

$$\begin{aligned} &\Lambda_0^0\to p+\tilde{\Pi}^- \quad (N_1\to N_0+\Pi_1),\\ &\Lambda_1\to\Lambda_0+\pi \quad (N_1'\to N_1+\Pi_0), \end{aligned} \tag{4·12}$$

are forbidden energetically. Hence V particles should decay slowly through odd interactions

$$\begin{aligned} &\Lambda_0^0\to p+\pi^- \quad (N_1\to N_0+\Pi_0),\\ &\Pi^0\to\pi^++\pi^- \quad (\Pi_1\to\Pi_0+\Pi_0). \end{aligned} \tag{4·14}$$

It is characteristic of the even-odd rule that the V particles should be produced in pairs, which is supported by the recent Cosmotron experiments

$$\pi^-+p\to\Lambda_0^0+\theta^0 \quad (\Pi_0+N_0\to N_1+\Pi_1). \tag{4·14}$$

(V) The conservation theorem of η-charge can account for the nature of V particles more adequately than the even-odd rule.[1),2)]

(i) The cascade decay of Y^-

$$Y^-\to\Lambda_0^0+\pi^-, \quad (\Lambda_0^0\to p+\pi^-) \tag{4·15}$$

cannot be accouted for by the even-odd rule.

If Y^- were odd the process (4·15) takes place through an even interaction so that its observed stability could not be guaranteed. If on the contrary Y^- were even, the process

$$Y^-\to n+\pi^- \tag{4·16}$$

would have to be fast. In either case the stability of Y^- could not be proved.

The η-charge conservation law can forbid the processes

$$\begin{aligned} &Y^-\to\Lambda_0^0+\pi^-, \quad Y^-\to n+\pi^-\\ &-2 \text{ or } -3,\ -1,\ 0 \quad -2 \text{ or } -3,0,\ 0 \end{aligned}$$

to occur rapidly through even interactions alone.[2),22)]

While the conservative process

$$\begin{aligned} &Y^-\to\Lambda_0^0+\tilde{\Pi}^-\\ &-2 \quad -1 \quad -1 \end{aligned}$$

is forbidden due to the energy conservation.

Suppose that Y^- belongs to the group G_2, *i.e.* Y^0 and Y^- form a charge doublet,

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then the observability of Y^0 must be discussed. It is natural to assume that Y^0 may decay as

$$Y^0 \to \Lambda_0^0 + \pi^0 \tag{4·17}$$

as compared to (4·15), but the decay can hardly be observed.

If, on the other hand, Y^0 decayed as

$$Y^0 \to p + \pi^-, \tag{4·18}$$

it would have to be observed experimentally.

So far there has been no evidence in favour of the decay modes (4·16) and (4·18), though not decisive because of the poor statistics, so that it will be instructive to impose a new selection rule[2] upon the odd interactions in the form

$$\Delta\eta = 0, \ \pm 1 .* \tag{4·19}$$

Then the processes

$$\begin{array}{c} Y^0 \to p + \pi^-, \\ Y^- \to n + \pi^- \\ (\eta) \quad -2 \quad 0 \quad 0 \end{array}$$

are forbidden in virtue of (4·19) since we have $\Delta\eta = 2$ for the above processes.

(ii) It is characteristic of the Cosmotron experiments that V particles are more copiously produced in pion-nucleon collisions[8] than in nucleon-nucleon collisions.[9] This can be attributed to the fact that the process with the lowest threshold energy

$$\begin{array}{c} N + N \to \Lambda + \Lambda \\ 0 \quad 0 \quad -1 \quad -1 \end{array} \tag{4·20}$$

is forbidden by the η-charge conservation law.[1),2),16),22)]

We tabulate the threshold energies of possible production processes which are expected to occur at Cosmotron energies.

Table I

Threshold Kinetic Energies of Production Processes of Λ and Π.

Process	E_{th}* (c.m.)	E_{th} (lab.)
$\pi + N \to \Lambda + \Pi$	516 Mev	760 Mev
$\pi + N \to N + \Pi + \tilde{\Pi}$	672 „	1357 „
$N + N \to \Lambda + N + \Pi$	335 „	1581 „
$N + N \to N + N + \Pi + \tilde{\Pi}$	493 „	2490 „

In this table Λ denotes either Λ_0 or Λ_1 but the calculations are made for the Λ_0 mass.

In nucleon-nucleus collisions the threshold energies of the production are lower than those in nucleon-nucleon collisions so that hyperons can more easily be produced in nucleon-nucleus collisions than in nucleon-nucleon collisions in conformity with the experimental material.[10]

(iii) It is remarked by several authors that comparatively long lived S particles[23] or

* This is an analogue of the isotopic spin selection rule

$$\Delta I = 0, \ \pm 1$$

for the electromagnetic interaction.

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some of the K particles observed in photographic emulsion[24] exhibit a large preponderance of positive ones over negative. This tendency can also be understood on the basis of the η-charge conservation law provided that these particles are identical with the Π-mesons.[1]

For simplicity we shall confine ourselves to π, N, Π and Λ, then the η-charge of this system is expressed by

$$\eta = n(\Pi_1) - n(N_1), \tag{4·21}$$

where

$$n(\Pi_1) = n(\Pi^+, \Pi^0) - n(\tilde{\Pi}^-, \tilde{\Pi}^0),$$
$$n(N_1) = n(\Lambda) - n(\tilde{\Lambda}).$$

V particles are generally produced in pion-nucleus or nucleon-nucleus collisions so that we can put

$$\eta_{\text{initial}} = 0,$$

and from the conservation law, we have

$$\eta_{\text{final}} = 0.$$

Hence in the final state, we obtain a relation

$$n(\Pi^+, \Pi^0) = n(\tilde{\Pi}^-, \tilde{\Pi}^0) + n(\Lambda), \tag{4·22}$$

neglecting $\tilde{\Lambda}$.

Let the total number of produced V particles be $n(V)$, then we have from (4·22)

$$n(V) = n(\Pi^+, \Pi^0) + n(\tilde{\Pi}^-, \tilde{\Pi}^0) + n(\Lambda) = 2n(\Pi^+, \Pi^0).$$

Since Λ particles are more easily produced than the $\tilde{\Pi}$-mesons because of the lower excitation energy to transform a nucleon into a Λ particle, *i.e.*$\sim$180 Mev. for Λ_0 and $\sim$270 Mev. for Λ_1, than the energy required to create a heavy $\tilde{\Pi}$-meson, *i.e.*$\sim$490 Mev., the production of V particles may occur in such a manner as to make $n(\Lambda)$ as large as possible for a fixed value of $n(\tilde{\Pi}^-, \tilde{\Pi}^0) + n(\Lambda)$, *i.e.*

$$n(\Lambda) \gg n(\tilde{\Pi}^-, \tilde{\Pi}^0).$$

Combining this inequality with (4·22), we arrive at

$$n(\Pi^+, \Pi^0) \sim n(\Lambda) \gg n(\tilde{\Pi}^-, \tilde{\Pi}^0), \tag{4·23}$$

namely the positive Π-mesons are more copiously produced than the negative ones. However, there are some exceptions to the above arguments. First, there must be enough material nucleons to be transformed into Λ particles when Λ particles are multiply produced. Secondly, at extremely high energies ($\gg$10 Gev), the small energy difference between the excitation energies of a Λ and the rest mass of a $\tilde{\Pi}$ cannot play as decisive a rôle as discussed above.*

(VI) In some cases the ratio of cross-sections can be obtained with reference to the C.I. alone.

The ratio

$$\sigma(p+p \to d+\pi^+)/\sigma(n+p \to d+\pi^0) = 2 \tag{4·24}$$

* The author is indebted to Prof. Z. Koba on this point.

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is well known in the pion theory as a test for the C.I. hypothesis. There are similar examples in the case of V particles, and the simplest one is

$$\sigma(\tilde{\Pi}^- + n \to \Lambda_0^0 + \pi^-)/\sigma(\tilde{\Pi}^- + p \to \Lambda_0^0 + \pi^0) = 2\,. \tag{4·25}$$

The channel isotopic spin of the above processes is equal to unity. Besides, there are many equalities derived from the charge symmetry, *e.g.*

$$\sigma(\pi^- + p \to \Lambda_0^0 + \Pi^0) = \sigma(\pi^+ + n \to \Lambda_0^0 + \Pi^+)\,. \tag{4·26}$$

These relations would be susceptible of experimental tests.

(VII) *Some remarks on the Fukuda–Miyamoto theorem*[26]

(i) Let ϕ_A be the wave function of a neutral Boson A which is an eigenstate of the charge conjugation C, then we have

$$C(\phi_A) = \varepsilon_A \phi_A\,, \quad \varepsilon_A = \pm 1\,.$$

We call A even or odd according as $\varepsilon_A = 1$ or -1, *e.g.* π^0 is even and γ is odd. We can sometimes speak of the parity under charge conjugation not only for elementary Bosons but also for composite Bosons, for instance a positronium is even in the ${}^1S_0$ state and odd in the ${}^3S_1$ state.

The transitions

$$A + B + \cdots \;\to\; C + D + \cdots$$

among such neutral Bosons are forbidden by the conservation of parity under charge conjugation, if

$$\varepsilon_A \varepsilon_B \varepsilon_C \cdots = -1\,, \tag{4·27}$$

This theorem is usually expressed in the form

$$n(v) + n(t) = \text{odd} \quad \text{is forbidden,} \tag{4·27′}$$

where $n(v)$ and $n(t)$ denote the numbers of neutral Bosons participating in the process which couples to the nucleon (or baryon) with vector and tensor couplings, respectively.

To our regret this selection rule cannot be applied to the decays of neutral heavy mesons since they cannot be eigenstates of the operator C unless $\eta = 0$ as seen from

$$\eta C = -C\eta\,.$$

(ii) Similarly the conservation of charge parity[27] can forbid some transitions among Bosons with $I_3 = 0$. Since the charge parity is conserved only for charge symmetric interactions the disccussions here are restricted to charge independent interactions,* consequently the photon is excluded from our subject.

The charge symmetry operation T anti-commutes with I_3, *i.e.*

$$TI_3 = -I_3 T\,.$$

Hence a particle can be the eigenstate of T only if $I_3 = 0$ for which the eigenvalue of T is given by

$$T = (-1)^I, \tag{4·28}$$

---

* Charge symmetric interactions are not necessarily charge independent. However we shall consider them to be charge independent according to the classification of the elementary interactions in § 3.

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where I is the isotopic spin of the particle and $(-1)^I$ is the charge parity.

The transitions

$$A+B+\cdots \rightarrow C+D+\cdots$$

are forbidden for charge independent interactions by the conservation of charge parity if

$$T_A T_B C_C \cdots = -1,$$
$$\text{or} \quad I_A+I_B+I_C+\cdots=\text{odd}, \tag{4·29}$$

where T_A, T_B,$\cdots$ are the charge parities of A, B,$\cdots$ and I_A, I_B,$\cdots$ their isotopic spins. This theorem is also known by a more familiar expression

$$n(\tau_3)=\text{odd} \quad \text{is forbidden}, \tag{4·29′}$$

where $n(\tau_3)$ is the number of neutral Bosons coupled to the nucleon (or baryon) with the isotopic spin matrix τ_3.

This selection rule, too, cannot be applied to the Π–mesons since I_3 cannot be equal to zero for half-integral isotopic spins.

(iii) A particle which is neither the eigenstate of C nor that of T is sometimes the eigenstate of the product CT, for instance, it is the case for charged pions ($CT=-1$ for pions).

A selection rule similar to (i) and (ii) can be derived by referring to the operator CT, which is known in a special case by

$$n(v)+n(t)+n(\tau_3)=\text{odd} \quad \text{is forbidden}. \tag{4·30}$$

Again this selection rule cannot be applied to V particles since they are not eigenstates of CT as seen from Fig. 1 in § 4.

In this way we have arrived at a conclusion that the selection rules imposed by charge conjugation cannot be applied to the analysis of heavy mesons, and we should refer to more general invariance theorems such as the conservation of angular momentum and of parity against space reflection. Thus it is very hard to settle the types of heavy mesons, for instance, from the θ^0–mode of decay of a Π^0–meson

$$\Pi^0 \rightarrow \pi^+ + \pi^-,$$

we can infer that the possible types of Π^0 are

$$0^+,\ 1^-,\ 2^+,\ 3^-,\cdots\cdots. \tag{4·31}$$

It could be reduced into

$$0^+,\ 2^+,\ 4^+,\cdots$$

if another possible mode of decay of the Π^0–meson

$$\Pi^0 \rightarrow 2\pi^0$$

were experimentally established.

§ 5. Heavy nuclear fragments

One of the most remarkable phenomena recently established is the heavy nuclear fragment. Danysz and Pniewski[9] have found the spontaneous disintegration of a boron

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nucleus emitted as a fragment from the disintegration of a silver or a bromine nucleus. Inspite of its rather large Q value of about 50 Mev, it decayed after reaching the end of its range within a time $\sim 3\times 10^{-12}$ sec. If it were a highly excited state of the boron nucleus it would undergo a spontaneous decay within a quite short lifetime, say, $\sim 10^{-20}$ sec. and could not survive as long as 10^{-12} sec. Therefore they considered that a Λ_0^0 particle substitutes a nucleon in the fragment.

At present there are several examples and they seem to support this view, namely the order of Q–values of these examples are consistent with their hypothesis. We have now further precise measurements of the Q–values of heavy nuclear fragments from which we can estimate the binding energies of a Λ_0^0 particle in the fragments[5),6)] as described in § 2, *i.e.*$\sim$1.5 Mev in ${}^{+}H_1^3$ and $\sim$4 Mev in ${}^{+}He_2^4$. Another support in favour of this view is provided by the observation of Debenedetti and others.[7)] They have found a fragment ${}^{+}H_1^3$ emitted from a star together with a positive τ–meson, and this phenomenon is quite consistent with the above viewpoint on the basis of the pair production of the heavy unstable particles. It then gives rise to discussions whether or not the Λ_1 particle can be bound to form a heavy nuclear fragmens in a way similar to Λ_0. The answer is negative, since the Λ_1 particle, when bound to a nucleus, should decay within a quite short time emitting a virtual pion as

$$\Lambda_1 \to \Lambda_0 + \pi \tag{5·1}$$

and the virtual pion being subsequently absorbed by the residual nucleus producing a star. Shortly speaking, the fast process is expressed by

$$\Lambda_1 + N \to \Lambda_0 + N + \text{energy release.} \tag{5·2}$$

It is also the case for the Y particle, since it would be transformed through the process

$$Y + N \to \Lambda_0 + \Lambda_0 + \text{energy release.} \tag{5·3}$$

It is worth while to notice that the process (5·1) is energetically forbidden only when it is isolated.

In this section we shall present a semi-quantitative basis for the Danysz-Pniewski's view.

From the process (2·11) we shall take it for granted that there exists an elementary interaction of the type

$$N\Lambda_0\Pi\,. \tag{5·4}$$

On the other hand, the interaction

$$\Lambda_0\Lambda_0\pi$$

cannot be charge independent and hence cannot be strong. Thus the problem is to examine whether it is possible or not to account for the two quantities

(a) the cross-section of the process $\pi^- + p \to \Lambda_0^0 + \Pi^0$,

(b) the binding energy of the Λ_0^0 in a heavy nuclear fragment, *e.g.* ${}^{+}H_1^3$, with a unique value of the coupling constant of the interaction (5·4).

For simplicity we shall assume the Π–meson to be scalar, then the interaction (5·5) can be written more precisely as

$$H_{\text{int}} = g\bar{\psi}_N \Phi_\Pi \psi_\Lambda + \text{h.c.}, \tag{5·5}$$

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where ψ_N, ψ_Λ and Φ_Π are the wave functions of the nucleon, Λ_0 and Π, and

$$\bar{\psi}_N \Phi_\Pi = \bar{\psi}_p \Phi_{\Pi^+} + \bar{\psi}_n \Phi_{\Pi^0} .$$

Then the straightforward perturbation theory gives[28]

$$g^2/4\pi \sim 0.4 \qquad (5\cdot 6a)$$

for $\sigma(\pi^- + p \to \Lambda_0^0 + \Pi^0) \sim 1$ mb at 1.5 Gev., provided that the coupling constant for the pion-nucleon interaction (direct coupling) is given by

$$G^2/4\pi = 10 .$$

Similarly we have[28]

$$g^2/4\pi \sim 0.9^* \qquad (5\cdot 6a')$$

for the ratio (3·5), *i.e.*

$$\sigma(\pi^- + p \to \Lambda_0^0 + \Pi^0)/\sigma(\pi^- + p \to p + \pi^-) \sim 1/7.^*$$

In order to solve the problem of the heavy nuclear fragment we must first derive the potential between a Λ_0 and a nucleon which can be found to be

$$V_{\Lambda N} = \frac{g^2}{4\pi} P_x P_\sigma \frac{e^{-m_\Pi r}}{r} \qquad (5\cdot 7)$$

by iterating the interaction (5·5) as seen from Fig. 2.

With the potential (5·7) and the phenomenological neutron-proton potential, the binding energy of Λ_0^0 in a fragment ${}^+H_1^3$ composed of a proton, a neutron and a Λ_0^0 can be adjusted to fit the experimental value, *i.e.*$\sim$1.5 Mev, by choosing[28]

$$g^2/4\pi \sim 1.1 , \qquad (5\cdot 6b)$$

and furthermore it is found theoretically that the fragment ${}^+H_1^3$ has spin 1/2, even parity, and isotopic spin 0.

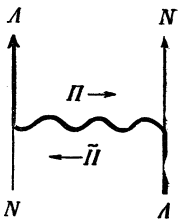

Fig. 2. Feynman diagram for the potential $V_{\Lambda N}$.

The above estimates are not quantitatively trustworthy since we have utilized the perturbation theory for strong interactions. We may, however, infer that the results are remarkably consistent with one another. Hence we may conclude that the Danysz-Pniewski's hypothesis is consistent with our present information on the V particles and that the coupling constant of the interaction (5·5) is roughly given by

$$g^2/4\pi \sim 1 . \qquad (5\cdot 8)$$

It is seen that the interaction (5·5) is considerably strong and that it will appreciably affect the pion reactions virtually. For instance, the contribution of the heavy particles to the anomalous magnetic moments of nucleons through the interaction (5·5) is roughly estimated on the perturbation theory to be[29]

$$\Delta\mu_p \sim 0.2 , \quad \Delta\mu_n = 0 , \qquad (5\cdot 9)^{**}$$

---

* If we employ the revised value of the ratio (3·5) to be 1/5 instead of 1/7, the coupling constant (5·6a′) may be 1.2. See footnote under (3·5) in § 3.

** **Note added in proof :** This result was revised as $\Delta\mu_p \sim -0.1$ by Iso in a private letter to the author.

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in the unit of nuclear magneton. Cf. Fig. 3.

In the case of proton, the contribution of these particles amounts to about 10% of the anomalous magnetic moment.

From the above calculations we see that the contributions of V particles to *pi*–mesonic phenomena are different from case to case due to the severe selection rules governing these particles, but we may conclude that in general we cannot ignore the presence of these particles for quantitative investigations of the pion-nucleon interaction.

We cannot discuss the pion-nucleon interaction without taking account of the influences of V particles. This is a situation sharply contrasted with quantum electrodynamics which is approximately a closed theory.

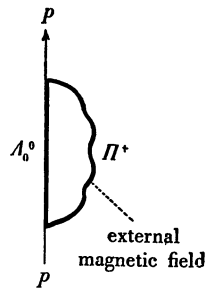

Fig. 3. Feynman diagram for the anomalous magnetic moment of a proton through the interaction (5·5). $\Delta\mu_n=0$ in this order.

§ 6. Possible models of the τ–mesons

In the previous sections, we have not touched upon the τ–meson. Indeed, inspite of its oldest career it is not an easy task to adapt the τ–meson definitely to the present C.I. scheme. We shall therefore discuss three possible models[30] of the τ–meson in the C.I. scheme.

Model I. (Π_1–model)

The most economical model is to regard the τ–meson as the charged counter particle of the θ^0–meson, *i.e.* $\tau^+=\Pi_1^+$. In this case, the heavy mesons Π_1^0 and Π_1^+ which decay through the modes

$$\Pi_1^0\to\pi^+ +\pi^-, \tag{6·1}$$

$$\Pi_1^+\to 2\pi^+ +\pi^- \text{ or } \pi^+ +2\pi^0 \tag{6·2}$$

are called θ^0 and τ^+, respectively.

The basis for this model consists in the equality of their masses

$$m_\tau = m_\theta . \tag{6·3}$$

As has been discussed in § 4, we can expect the positive excess of τ–mesons in conformity with the experimental material.

With reference to (6·1), we may suppose that the Π_1^+–meson will decay into two pions as well as into three pions, then the Π_1^+–meson decaying as

$$\Pi_1^+\to\pi^+ +\pi^0 \tag{6·4}$$

must be called with a name other than the τ–meson.

On the other hand it is reasonable to assume that Π_1^+–mesons and Π_1^0–mesons are produced with equal abundance and that the branching ratio $\Pi_1\to 2\pi$ to $\Pi_1\to 3\pi$ is much larger than unity.

Thus we can predict

$$(\text{abundance of } \theta^0)/(\text{abundance of } \tau^+)\sim\text{branching ratio } (\Pi_1\to 2\pi)/(\Pi_1\to 3\pi), \tag{6·5}$$

and consequently

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$$\text{abundance of } \theta^0 \gg \text{abundance of } \tau^+. \tag{6·6}$$

It is interesting to see that the above relations are roughly satisfied, though not decisive because of the poor statistics.

From the three pion decay of a τ–meson the Π_1–meson cannot be scalar (0^+), so that the possible types of the Π_1–meson are

$$1^-,\ 2^+,\ 3^-,\ 4^+,\cdots \tag{6·7}$$

in reference to (4·31).

However, there seems to be an objection against this model. In preliminary analysis of the τ–meson decay data Dalitz[31] has arrived at a conclusion against (6·7).

Model II. (Π_1'–model)

If we take Dalitz' objection seriously, the model I must be improved. The simplest modification is achieved by assuming the τ–meson to be a charge doublet of the group G_1 other than the Π_1–meson, *i.e.*

$$I=1/2 \text{ for } \tau^+ \text{ and } \tau^0. \tag{6·8}$$

Since $\eta=1$ for a τ–meson, we shall denote the τ–meson as Π_1' analogously to Π_1, then the nature of Π_1'–mesons is akin to that of Π_1–mesons so long as the C.I. is concerned, but their transformation properties in space-time are different from one another, contrary to the model I.

The observations by Debenedetti and others[7] provide one with a support in favour of the above two models.

Model III. (Π_2–model)

Another possibility is to assume

$$I=0 \text{ for } \tau^+, \text{ and hence } \eta=2. \tag{6·9}$$

In this case we cannot retain the selection rule (4·19)

$$\Delta\eta=0,\ \pm1$$

for the weak interactions since we have $\Delta\eta=-2$ for $\tau\to3\pi$. The τ–meson in this model will be denoted as Π_2.

Possible production processes of the Π_2–mesons and their threshold energies are tabulated in the Table II.

Table II*

Threshold Kinetic Energies of Production Processes of Π_2

Process	E_{th}* (c.m.)	E_{th} (lab.)
$\pi+N\to Y+\Pi_2$	649 Mev	1123 Mev
$\pi+N\to N+\Pi_2+\tilde{\Pi}_2$	672 ,,	1357 ,,
$N+N\to\Lambda+\Lambda+\Pi_2$	424 ,,	2078 ,,
$N+N\to N+N+\Pi_2+\tilde{\Pi}_2$	493 ,,	2490 ,,

In this Table II, just as in Table I, Λ denotes either Λ_0 or Λ_1 but the calculations are made for the Λ_0 mass.

It is interesting to see that the Π_2–meson still exhibits positive excess at low energies but its positive to negative ratio is expected to be smaller than that for the Π_1–meson since the argumentation of (V), (iii) in § 4

* The observation by Debenedetti and others[7] can be interpreted in terms of the third process of this table with a Λ_0^0 missed from their observation.

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loses its validity because of the double η–charge of Π_2.

The $\tilde{\Pi}_1^-$–meson can be absorbed by a nucleon through the process

$$\begin{array}{cccccc} & \tilde{\Pi}_1^- & + & p & \rightarrow & \Lambda_0^0 + \pi^0 \\ (\eta) & -1 & & 0 & & -1 \quad 0 \end{array} \tag{6·10}$$

even at zero energy.

On the contrary, $\tilde{\Pi}_2^-$ cannot be absorbed by a single nucleon since the absorption of a $\tilde{\Pi}_2^-$–meson from a Bohr orbit via

$$\begin{array}{cccccc} & \tilde{\Pi}_2^- & + & p & \rightarrow & Y^- + \pi^+ \\ & -2 & & 0 & & -2 \quad 0 \end{array} \tag{6·11}$$

or

$$\begin{array}{cccccc} & \tilde{\Pi}_2^- & + & p & \rightarrow & \Lambda_0^0 + \tilde{\Pi}_1^0 \\ & -2 & & 0 & & -1 \quad -1 \end{array} \tag{6·12}$$

is forbidden energetically. Absorptions through very weak interactions may occur, however, via other processes which are allowed energetically.

The situation is quite different for nuclei, *i.e.* the process

$$\begin{array}{cccccc} & \tilde{\Pi}_2^- & + & d & \rightarrow & \Lambda_0^0 + \Lambda_0^0 \\ & -2 & & 0 & & -1 \quad -1 \end{array} \tag{6·13}$$

can take place even at zero energy with an energy release of about 130 Mev. provided that Π_2 is not scalar.

The nature of the above process is very like the familiar process

$$\pi^- + d \rightarrow n + n\,. \tag{6·14}$$

We have presented here three possible C.I. models of the τ–mesons but we need further precise measurements to settle which of the above three or none of them is the correct one.

In conclusion the author expresses his sincere thanks to many physicists who gathered at the Research Institute for Fundamental Physics for their helpful discussions and to Prof. S. Hayakawa for his careful reading of the manuscript.

Note added after the completion of the manuscript

(1) Fry and Swami observed a heavy nuclear fragment in which possibly a θ^0–meson was bound. W.F. Fry and M.S. Swami, Phys. Rev. **96** (1954), 809.

(2) Naugle and others have observed an interaction caused by a stopping heavy meson in emulsion. One of the four particles emitted in the interaction is interpreted as a nuclear fragment with a Λ_0^0 attached. This evidence provides us with a strong support in favour of the Danysz-Pniewski's hypothesis together with the De Staebler's observation.

J.E. Naugle et al., Phys. Rev. **96** (1954), 1383.

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