The Processes of Production of Heavy Mesons and V_1^0-Particles *

B. M. PONTECORVO
Institute of Nuclear Problems, Academy of Sciences, USSR
(Submitted to JETP editor April 30, 1955)
J. Exper. Theoret. Phys. USSR 29, 140-146 (August, 1955)

Production processes of V_1^0-particles and heavy mesons are considered from a phenomenological point of view. A mechanism for associated production of V-particles and heavy mesons is discussed. The possibility is estimated for relatively stable systems to exist, composed of nucleons and V-particles. Detailed consideration is given to the difficulties connected with the existence of particles which are produced in abundance but have a long lifetime.

The conclusions which are reached may help in forming working hypotheses for the interpretation of experimental data and for the design of experiments on the production of the new particles.

1. NUCLEONIC CHARGE

IN considering the problem of the production of V_1^0-particles and heavy mesons, it is convenient to use the concept of "nucleonic charge". According to Zel'dovich[3], a nucleon has nucleonic charge $+\gamma$, an antinucleon $-\gamma$, and the pion, muon, electron, photon and neutrino have nucleonic charge zero. The total nucleonic charge is conserved in nuclear reactions. This principle expresses the fact that nuclear matter is stable. In particular, it states that a nucleon cannot transform into an antinucleon, nor decay into exclusively light particles. The concept of nucleonic charge is especially useful for describing the V_1^0-particle which decays into a proton and a pion. The V_1^0-particle, and in general all "heavy nucleons", must have nucleonic charge $+\gamma$.

2. NOTATION

We mention the question of notation, because the literature discussing the single and associated production of particles contains many ambiguous expressions. Any virtual transformation of a nucleon, occurring as a first-order process in perturbation theory, we shall represent by the following general scheme:

A		B		C	(1)
(nucleon)	$\to$	(one particle with nucleonic charge $+\gamma$)	+	(one or more particles with total nucleonic charge zero)	

The order of magnitude of the admixture of the state $(B+C)$ in the state of the nucleon defines the development-parameter of the perturbation theory. In the case when the system C consists of a single particle, the development-parameter may be written in the form $g^2/\hbar c$, where g has the dimension of charge. In this terminology the expressions "single production", "double production", etc., will refer only to the term C of scheme (1).

It should be emphasized that the scheme (1) describes only reactions which have non-vanishing matrix elements in the first approximation. For example, the Yukawa process

$$(N) \to (N) + (\pi) \quad (N = \text{nucleon})$$

describes "single production" of pions.

3. LIFETIME OF HEAVY MESONS

We shall begin with the question of the neutral pion decay. The neutral pion decay is generally considered as a 3-step process. The first step, the creation of a virtual proton-antiproton pair, follows directly from the possibility of the Yukawa process. In third-order perturbation theory the meson decay is described as follows:

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* This paper is based on the results of work completed in 1951-1953 and already published in reports of the Institute of Nuclear Problems[1,2]. The exposition will follow the second report[2], and the nomenclature for the various particles which was current at that time will be retained.

[1] B. M. Pontecorvo, Report Inst. Nuclear Prob., Acad. Sci., USSR (1951)

[2] B. M. Pontecorvo, Report Inst. Nuclear Prob., Acad. Sci., USSR (1953)

[3] Ia. B. Zel'dovich, Dokl. Akad. Nauk SSSR 86, 505 (1952)

$$\pi^0 \underset{g_\pi^2}{\longrightarrow} (P_1 + \tilde{P}_2) \underset{e^2}{\longrightarrow} (P_2 + \gamma_1 + \tilde{P}_1) \underset{e^2}{\longrightarrow} \gamma_1 + \gamma_2. \quad (2)$$

The probability $(1/t)_{\pi^0}$ of process (2) occurring per unit time must involve the product $(g_\pi^2/\hbar c) \times (e^2/\hbar c)^2$ The interaction of the neutral pion with the electromagnetic field, which is manifested in the two-photon decay, arises from its coupling to the "proton vacuum". In a similar way we shall later use the idea of the coupling of other mesons to the "nucleon vacuum" in order to draw conclusions about the production mechanism of these mesons.

A very interesting fact to which we must give our attention is the following: there exist several types of mesons which are produced with high probability and have a relatively long lifetime ($t \gg 10^{-10}$ sec) against decay into pions. We denote such particles* by the letter τ and call them mesons of the class τ. As we shall now show, it follows from the definition that mesons of the class τ cannot be created singly in virtual processes in which a nucleon remains a nucleon. In other words, the fundamental reaction of the mucleon in which mesons of class τ are created cannot arise from the scheme

$$(N) \rightarrow (N) + (\tau). \quad (3)$$

In fact, if mesons of the class τ (for example, τ^+-mesons) were produced by the process (3), we could write

$$\tau^+ \underset{g^2_\tau}{\longrightarrow} (P_1 + \tilde{n}_1) \underset{g^2_\pi}{\longrightarrow} (n_1 + \pi_1^+ + \tilde{n}_1) \underset{g^2_\pi}{\longrightarrow} \quad (4)$$
$$\rightarrow (n_1 + \pi_1^+ + P_1 + \pi_2^+) \underset{g^2_\pi}{\longrightarrow} \pi^+ + \pi^+ + \pi^-.$$

Here the last three steps go with the parameter $(g^2_\pi/\hbar c)$, and the first goes with the parameter $(g^2_\tau/\hbar c)$ which describes the strength of the coupling between the class τ meson and the nucleon. Assuming scheme (3) to hold, the parameter $(g^2_\tau/\hbar c)$ can be roughly estimated from the known ratio of the production probabilities of pions and mesons of class τ. This gives $(g^2_\tau/g^2_\pi) \gtrsim 0.01$. A comparison of processes (2) and (4) then shows that the lifetime of class τ mesons should be shorter than that of the neutral pion (10^{-14} sec), in sharp contradiction with experiment. Therefore, process (3) is not responsible for the production of class τ mesons, unless the production cross section of class τ mesons has such an extreme dependence on energy that the use of the principle of detailed balance is unjustified.

Moreover, the long lifetime of the charged pion itself ($t_{\pi^\pm} \sim 2 \times 10^{-8}$ sec) shows that there does not exist a particle ϵ, with mass less than say $0.3\, m_\pi$, strongly coupled to the nucleon by the scheme

$$(N) \rightarrow (N) + (\varepsilon).$$

4. INADEQUACY OF A PROPOSAL FOR INDIRECT PRODUCTION OF CLASS τ MESONS

At first glance, the contradiction between the abundant production and long lifetime of class τ mesons might seem to be resolved by postulating a heavier meson θ, which would decay with emission of a class τ meson and would be produced according to the scheme

$$(N) \rightarrow (N) + (\theta). \quad (5)$$

However, on this hypothesis, an argument similar to the one which led to the earlier paradox shows that the rate of decay of the θ-meson into pions must be very large. This decay rate must in turn be comparable with the rate of the θ-meson decay which emits a class τ meson, in order that the latter particle be observed. Then, through the intermediate creation of a virtual θ-meson, the class τ meson would decay rapidly into pions, in contradiction with experiment. Hence, the process (5) cannot describe the (indirect) production of class τ mesons.

5. POSSIBLE EXPLANATIONS OF THE LONG LIFETIME OF CLASS τ MESONS

To resolve the contradiction between the abundant production and the long lifetime of class τ mesons, we consider two possibilities for the production process:

a) The class τ meson is produced in pairs with another particle, for example,

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* The following[4] are mesons of the class τ: τ-meson ($m_\tau = 980\, m_e$), V_2^0-meson ($m_{V_2^0} \sim 800\, m_e$), χ-meson ($m_\chi \sim 1500\, m_e$), ζ-meson ($m_\zeta = 540\, m_e$). It is probable that the mesons with mass 500-600 m_e observed by Alikhanian et al[5] also belong to the class τ. But this cannot be stated with certainty, since it is not known whether these mesons decay into pions.

[4] See, for example, R. Daniel et al, Phil. Mag. 43, 753 (1952)

[5] A. I. Alikhanian, J. Exper. Theoret. Phys. USSR 21, 1062 (1951)

$$(N) \to (N) + (\tau + ?), \qquad (6)$$

however, this possibility, production of integer-spin particles in pairs, seems very artificial.

b) Mesons of class τ are produced singly, but the associated particles with nucleonic charge $+y$ are not ordinary nucleons:

$$(N) \to (\text{heavy nucleon}) + (\tau). \qquad (7)$$

In this case, the mesons can clearly be produced abundantly and yet have a long lifetime. This scheme seems logically the most satisfactory. We will return to it after considering the origin of V_1^0-particles.

6. LIFETIME OF V_1^0-PARTICLES

Just as for class τ mesons, there is a contradiction between the abundant production and long lifetime of V_1^0-particles. The probability of the process

$$V_1^0 \to P + \pi^- \qquad (8)$$

is only 3×10^9 sec^{-1}. It is obvious that the V_1^0-particle cannot originate in the same reaction which produces pions. In other words, a reaction of the type

$$(N) \to (V_1^0) + (\pi) \qquad (9)$$

is not responsible for the production of V_1^0-particles. This conclusion is made with the same reservation, about the applicability of the principle of detailed balance, as the similar conclusion in Sec. 3 about the production of class τ mesons.

The proposal that the V_1^0-particle is produced together with a pair of pions

$$(N) \to (V_1^0) + (\pi + \pi).$$

is equally unsatisfactory. It would be difficult to imagine a mechanism which would allow production of pions in pairs and forbid single production.

We discuss next the case in which two particles are created with opposite nucleonic charge. There are the following possibilities*

	A		B	C
a)	(N)	$\to$	(N)	$+ (V_1^0 + \tilde{V}_1^0)$,
b)	(N)	$\to$	(N)	$+ (V_1^0 + \tilde{N})$,
c)	(N)	$\to$	(V_1^0)	$+ (V_1^0 + \tilde{N})$.

Reaction (b) cannot be responsible for the production of V_1^0-particles. By an argument similar to that used earlier, it can be shown that (b) implies a lifetime of the V_1^0-particle much shorter than is observed. Reaction (a) implies an equally abundant production of V_1^0 and anti-V_1^0-particles. If anti-V_1^0-particles were actually produced, it should not be especially difficult to observe them. The fact that they have not yet been observed speaks against reaction (a).

According to experiment[6], two V_1^0-particles are not commonly produced in a single act. Hence, reaction (c) also cannot be responsible for the production of V_1^0-particles.

Therefore, it is reasonable to postulate that in the production of V_1^0-particles according to scheme (1) there appears a second particle, different from the pion, having integer spin and zero nucleonic charge:

A		B		C	
(N)	$\to$	(V_1^0)	$+$	(Charged meson different from the pion, with nucleonic charge zero).	(10)

It is interesting to notice that in Sec. 5 we arrived at a similar scheme (7) in order to explain the long lifetime of the class τ meson.

7. CONNECTION BETWEEN CLASS τ MESONS AND V-PARTICLES

It is natural to identify the "heavy nucleon" in Eq. (7) with the V_1^0-particle and the "charged integer-spin meson" in Eq. (10) with the class τ meson. Then we obtain the following reaction scheme.

$$(N) \to (V_1^0) + (\tau). \qquad (11)$$

This removes simultaneously the contradiction between abundant production and long lifetime, both for particles of class V and class τ. Our argument assumes a moderately large value for the development parameter corresponding to reaction (11). Nucleonic reactions in which pions are produced together with V-particles, and reactions in which class τ mesons are produced without V-particles, are expected to be extremely improbable. Schematically,

* For simplicity, we do not here envisage the existence of heavy charged V-particles.

[6] R. Leighton et al, Phys. Rev. 89, 148 (1953)

$$(N) \overset{\text{yes}}{\rightarrow} (V_1^0) + (\tau), \qquad (12)$$
$$(N) \overset{\text{no}}{\rightarrow} (V_1^0) + (\pi),$$
$$(N) \overset{\text{no}}{\rightarrow} (N) + (\tau).$$

It must be mentioned that in photographs[6] of the V_1^0-decay, tracks of decaying charged mesons of class τ have not been seen. If scheme (12) is correct, this probably means that the class τ meson is either neutral, or is charged and has a lifetime longer than 10^{-9} sec (the length of track before decay must be longer than the size of the Wilson chamber). In this connection, the observation[5,7] of charged mesons with mass greater than 500 m_e, and with a lifetime 10^{-8} - 10^{-9} sec, is of interest.

The symbol V_1^0 in (11) and (12) denotes the well-known neutral particle which decays into proton and pion. By "heavy nucleons of the class V" we shall mean any long-lived particles which have nucleons among their decay-products. Then we may postulate the more general reaction scheme *

$$\begin{matrix} A & & B & & C \\ (N) & \rightarrow & (V) & + & (\tau) \end{matrix} \qquad (13)$$

It would be premature to consider the precise identification of particles B and C in (13).

The scheme (13) is in some respects similar to the scheme of Yukawa. The class τ meson will cause interaction between nucleons and V-particles, just as the pion causes interaction between ordinary nucleons. This idea is interesting in connection with the possible existence of metastable systems composed of nucleons and V-particles, which will be discussed in the next Section.

8. METASTABLE SYSTEMS COMPOSED OF ORDINARY AND HEAVY NUCLEONS

In the recent literature[9] there have appeared reports of a very interesting phenomenon in high-energy nuclear interactions. In photographic emulsions three cases have been observed of stars which contained, in addition to normal tracks, a single track of a particle which came to rest in the emulsion and gave rise to a secondary star at the point where it stopped. Such a track, in the opinion of the authors, is caused by a "nucleus containing a V_1^0-particle", and the secondary star is caused by the decay of the particle within the nucleus. This proposal deserves attention. As we shall see, the existence of metastable systems composed of nucleons and V-particles is definitely to be expected, if the scheme (13) is correct.

We consider the interaction between a particle of the class V (for simplicity, we shall speak about the V_1^0-particle) and a nucleon, assuming that the rules (12) apply. Since in (12) a class τ meson is responsible for a strong interaction between nucleons and V_1^0-particles, the collision cross section between a V_1^0-particle and a nucleon must be relatively large. When the relative energy of a V_1^0-particle and nucleon is small, only elastic collisions are possible *, while at sufficiently high energies there will also be inelastic collisions accompanied by the creation of a class τ meson. If the forces between nucleon and V_1^0-particle are attractive, then the V_1^0 particle under favorable conditions may be bound with nucleons into a quasi-nuclear system.

We now estimate the degree of stability of such a quasi-nuclear system. The mean energy of a particle bound within the sytem is determined by the temperature of the quasi-nucleus, and is therefore small in comparison with the energy required according to (12) for an inelastic collision of a nucleon and a V_1^0-particle, i.e., a collision in which a class τ meson is produced. Thus, a V_1^0-particle in the quasi-nucleus does not lose its individuality, and decays essentially as if it were free.

We consider now the observed events[9] in more detail. In our scheme a V_1^0-particle is produced together with a class τ meson. The track of the meson is probably one of the relativistic tracks in the shower. The V_1^0-particle is rapidly slowed down by multiple elastic scattering in nuclear matter until further inelastic processes are impossible. This phase of the phenomenon is similar to

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* Similar schemes have been proposed independently by several other authors. See, for example, Pais[8].

7 J. Astbury et al, Phil. Mag. 44, 242 (1953)

8 A. Pais, Phys. Rev. 86, 663 (1952)

9 M. Danysz and J. Pniewski, Phil. Mag. 44, 348 (1953); D. Tidman et al, Phil. Mag. 44, 350 (1953); J. Crussard and D. Morellet, Comptes Rendus 236, 64 (1953)

* The long lifetime of the V_1^0-particle implies that it cannot decay into a nucleon and a class τ meson. If (12) is correct, this decay is forbidden only by energy conservation. In other words, the mass of a class τ meson occurring in (12) must be greater than ($m_{V_1^0} - m_p$), i.e., $m_\tau > 400\ m_e$.

the well-known process of the nucleonic cascade in nuclear matter. Afterwards, a light quasi-nucleus is emitted containing the V_1^0-particle. At this stage the phenomenon is similar to the emission of nuclear fragments (He, Li, B, etc.) from excited nuclei. Next, the quasi-nucleus is slowed down by ionization energy-loss. The slowing-down time is short compared with the lifetime of the V_1^0-particle, which therefore decays within a stationary quasi-nucleus.

It is worth noting that process of the type $(N) \rightarrow (V_1^0) + (\pi)$ cannot be consistent with the stability of systems composed of nucleons and V_1^0-particles. We already found that the existence of such a process would lead to difficulties in explaining the long lifetime of the free V_1^0-particle. If we admit such a process, it seems completely impossible to imagine a mechanism which would allow the V_1^0-particle to survive for a long time in nuclear matter.

Consequently, if the existence of metastable systems composed of nucleons and V-particles is confirmed, it provides a powerful argument in support of the scheme (13).

CONCLUSIONS

1) Starting from the fact that in high-energy collisions there is abundant production of mesons (of the class τ) which have a long lifetime and decay into pions, one can deduce that the production of these mesons cannot proceed by the scheme

$$(N) \rightarrow (N) + (\tau) \quad (N \equiv \text{nucleon}).$$

2. Similarly, starting from the fact that in high-energy collisions there is abundant production of heavy nucleons of the class V which have a long lifetime and decay into nucleons and pions, one can deduce that the production process for these particles is not

$$(N) \rightarrow (V) + (\pi).$$

3. It is proposed that class τ mesons and heavy nucleons of the class V are produced together by the scheme

$$(N) \rightarrow (V) + (\tau).$$

Then the difficulties arising from the long lifetimes of V-particles and of class τ mesons are simultaneously resolved. In addition, this scheme predicts a strong interaction, mediated by class τ mesons, between nucleons and V-particles.

4. If the scheme $(N) \rightarrow (V) + (\tau)$ is correct, one must expect under favorable conditions the formation of metastable systems composed of nucleons and V-particles.

In conclusion, I wish to thank I. Ia. Pomeranchuk for several valuable discussions.

Translated by F. J. Dyson
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