Note on the Decay and Absorption of the θ^0†

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A suggestion is made on how to verify experimentally a recent theoretical suggestion that the θ^0 meson is a "particle mixture."

IT is the purpose of this note to indicate a further consequence of a recent theoretical suggestion[1] concerning the properties of the θ^0. The point to be made here is of some interest in that it leads to possible experimental tests of the ideas outlined in I.

A reaction in which the θ^0 is produced is[2]

$$\pi^- + p \rightarrow \Lambda^0 + \theta^0. \tag{1}$$

Its decay properties have been discussed in I starting from two assumptions:

(a) The θ^0 is distinct from its antiparticle $\bar{\theta}^0$. This property of the θ^0 reconciles the occurrence of the reaction (1) with the apparent nonoccurrence[3] of $n+n\rightarrow \Lambda^0+\Lambda^0$, ($n$=neutron). Certain models which have been proposed for the classification of some of the properties of the new particles[4] embody this distinction between the θ^0 and the $\bar{\theta}^0$.

(b) The rigorous validity of charge conjugation invariance.

Let us call θ_1^0 the particle that decays according to

$$\theta_1^0 \rightarrow \pi^+ + \pi^- + 215 \text{ Mev}, \tag{2}$$

with a mean life $\tau_1 \sim 1.5\times 10^{-10}$ sec. On the basis of the assumptions (a) and (b) it was argued in I that the θ^0 as produced for example in reaction (1) cannot be identical with the θ_1^0 decaying according to (2). It was shown that one rather has to consider the θ^0 as a "particle mixture" of θ_1^0 and a hypothetical second neutral particle θ_2^0. The main distinctive feature of θ_1^0 and θ_2^0 is that the set of decay channels that are allowed for the θ_1^0 are forbidden for the θ_2^0. Thus the lifetime τ_2 of the θ_2^0 should be different from τ_1. It is impossible at the present theoretical stage to predict the lifetime of the assumed θ_2^0. However it has been suggested tentatively in I that the θ_2^0 should live considerably longer than the θ_1^0.

The distinct lifetimes of the θ_1^0 and the θ_2^0 must be due to distinct decay interactions for these particles. Therefore the respective masses M_1, M_2 of these two particles are not strictly equal. But as the decay interactions are very weak, the mass difference $M=M_1-M_2$ will be correspondingly small. Its order of magnitude will presumably be given by $c^2\Delta M\tau_1/\hbar\sim 1$, i.e., $c^2\Delta M \sim 10^{-5}$ ev. It is nevertheless not inconceivable that such a tiny mass shift could give rise to effects observable in practice [see the discussion of Eqs. (10) and (11) below]. It may be recalled from I that the spin and parity of the θ_2^0 should be the same as for the θ_1^0.

More precisely, this notion of particle mixture means the following: At production the wave function $\langle\theta^0\rangle$ describing a given θ^0 state is a well-defined superposition of two wave functions $\langle\theta_1^0\rangle$ and $\langle\theta_2^0\rangle$ describing respectively the two particles θ_1^0 and θ_2^0 in the same state. (A given state can for example refer to a prescribed momentum and, if the spin of the θ^0 is unequal to zero, to a given spin direction.) The superposition is in fact[5]

$$\langle\theta^0\rangle = (\langle\theta_1^0\rangle \pm i\langle\theta_2^0\rangle)/\sqrt{2}. \tag{3}$$

As can be seen from I, the plus or minus sign holds true according to whether the parity of the θ^0 is even or odd.[6] The subsequent argument does not depend on the parity of the θ^0 and for the sake of definiteness we shall carry the plus sign from now on. Quite similarly the $\bar{\theta}^0$ is a particle mixture, but with a relative phase

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[1] M. Gell-Mann and A. Pais, Phys. Rev. 97, 1387 (1955); henceforward referred to as I.

[2] Fowler, Shutt, Thorndike, Whittemore, Phys. Rev. 91, 1287 (1953); Phys. Rev. 93, 861 (1954).

[3] Experimental results with the Brookhaven Cosmotron show that the cross section for Λ^0 production is $\sim$1 mb/nucleon when the available energy is definitely above the threshold for production of $\Lambda^0+\theta^0$ such as for the 1.47-Bev π^- beam, or 2.7-Bev proton beam. On the other hand, at energies less than the threshold for $\Lambda^0+\theta^0$, but definitely larger than the threshold for $\Lambda^0+\Lambda^0$ (neutrons of energy somewhat larger than 1 Bev), the cross section for Λ^0 production seems to be much smaller than 0.1 mb/nucleon. This is taken as an indication (not as a proof) that the reaction $n+n\rightarrow\Lambda^0+\Lambda^0$ is probably forbidden. See papers by R. Shutt and by G. Collins, Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics (Interscience Publishers, Inc., New York, 1955). We thank Dr. R. Shutt, Dr. A. Thorndike, Dr. W. Whittemore, Dr. E. Fowler, and Dr. H. Kraybill for a very helpful discussion on this subject.

[4] For a recent survey of these models and their inter-relations see A. Pais, Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics (Interscience Publishers, Inc., New York, 1955).

[5] This implies that we ignore the influence of the weak decay interactions on the production of the θ^0.

[6] As was pointed out in I, the relative phase of $\langle\theta_1^0\rangle$ and $\langle\theta_2^0\rangle$ is determined from the requirement of charge conjugation invariance. To avoid confusion we note that the language of the present note differs on one point from that of I: here we define θ_1^0 as the particle for which the decay process (2) is allowed. In I the θ_1^0 was defined as the particle with charge conjugation quantum number +1.

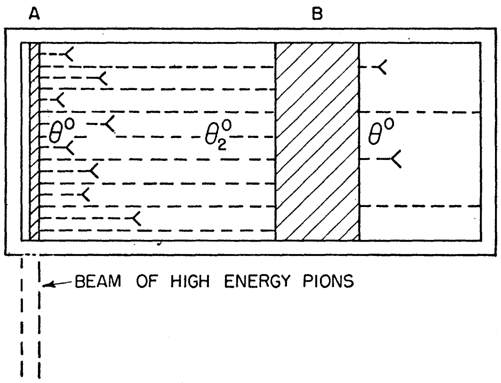

FIG. 1. Schematic diagram showing the regeneration of $\theta_1{}^0$ events in a multiplate cloud chamber. The symbol ---< indicates the decay: $\theta_1{}^0 \to \pi^+ + \pi^-$.

different from that of the θ^0 mixture:

$$\langle \bar{\theta}^0 \rangle = (\langle \theta_1{}^0 \rangle - i \langle \theta_2{}^0 \rangle)/\sqrt{2}. \quad (4)$$

$\bar{\theta}^0$ will thus exhibit the same decay modes and mean lives that θ^0 does. However, the strong interactions[7] of these two particle mixtures with nuclear matter are quite distinct: It is at once evident from the fact that reaction (1) has a sizeable cross section ($\sim$1 mb at 1.5 Bev π energy) that the processes

$$\bar{\theta}^0 + p \to \Lambda^0 + \pi^+, \quad (5)$$

and

$$\bar{\theta}^0 + n \to \Lambda^0 + \pi^0 \quad (6)$$

must be quite probable too. The isotopic spin value attributed[3] to $\bar{\theta}^0$: $I=\frac{1}{2}$, $I_3=\frac{1}{2}$, actually suggests that process (5) is twice as probable as process (6). Reactions similar to (5) and (6) should also occur with the production of $\Sigma^{+,0,-}$ instead of Λ^0. Another mode of strong interaction of the $\bar{\theta}^0$ with nucleons is charge-exchange scattering of the type

$$\bar{\theta}^0 + n \to p + \theta^-. \quad (7)$$

On the other hand, if the suggested selection rules for strong interactions[3] are correct, the θ^0 cannot be absorbed by processes of the type (5), and (6). Exchange scatterings like

$$\theta^0 + p \to n + \theta^+ \quad (8)$$

are allowed, however. Thus the $\bar{\theta}^0$ should have an absorption cross section of the order of nuclear size, while the θ^0 should disappear with a much smaller cross section.

It is conceivable that some of the anomalous cases of θ^0 decays reported in the literature[8] represent $\theta_2{}^0$ decays and a careful investigation of more such cases might furnish information about the existence and decay modes of this so far hypothetical particle. The number of anomalous θ^0 decays observed in an experimental arrangement suited for the observation of $\theta_1{}^0$ should be relatively more important the more nearly τ_2 would be equal to τ_1. If however, as has been surmised in I, τ_2 is considerably larger than τ_1, a direct observation of $\theta_2{}^0$ decay would be less practical. This situation would, on the other hand, provide the best conditions for the experiment that we are going to propose. In this experiment it is not required to observe a novel mode of decay.

Suppose that a cloud chamber contains two plates A and B, shown in their cross section in Fig. 1. The thin plate A is bombarded by high-energy nucleons, or, perhaps better, by fast negative pions. Then θ^0's will be produced and some of them will be observed, at about 90° to the beam, by their decay into two charged pions. The population of $\theta_1{}^0$ decays will decrease with a composite mean free path (the energy of the particles will not be unique) of the order of a few centimeters. As time elapses, the wave function thus changes its composition because of the different lifetimes of the $\theta_1{}^0$ and the $\theta_2{}^0$. For such later times the wave function can be written as

$$\{\langle \theta_1{}^0 \rangle e^{-t/2\tau_1 + i\omega_1 t} + i \langle \theta_2{}^0 \rangle e^{-t/2\tau_2 + i\omega_2 t}\}/\sqrt{2}$$
$$= \{[\langle \theta^0 \rangle + \langle \bar{\theta}^0 \rangle] e^{-t/2\tau_1 + i\omega_1 t} + [\langle \theta^0 \rangle - \langle \bar{\theta}^0 \rangle] \times e^{-t/2\tau_2 + i\omega_2 t}\}/2, \quad (9)$$

where $\hbar\omega_i = c(p^2 + M_i{}^2 c^2)^{\frac{1}{2}}$, $i=1, 2$. Thus we are now no longer dealing with a pure θ^0 state which (see I) is always composed of a $\theta_1{}^0$ state and a $\theta_2{}^0$ state with equal amplitudes. Note that $\omega_1 - \omega_2 \simeq c^2 \Delta M/\hbar$; therefore the probabilities $P(\theta^0, t)$ and $P(\bar{\theta}^0, t)$ of finding respectively a θ^0 or a $\bar{\theta}^0$ at time t can be written as

$$P(\theta^0, t) = \tfrac{1}{4} N [e^{-t/\tau_1} + e^{-t/\tau_2} + 2e^{-t/2\tau_1 - t/2\tau_2} \times \cos c^2 \Delta M t/\hbar], \quad (10)$$

$$P(\bar{\theta}^0, t) = \tfrac{1}{4} N [e^{-t/\tau_1} + e^{-t/\tau_2} - 2e^{-t/2\tau_1 - t/2\tau_2} \times \cos c^2 \Delta M t/\hbar], \quad (11)$$

where N is the density of the initially produced θ^0 beam. The third term in (10) and in (11) shows a (damped) oscillatory behavior which, for times such that $c^2 \Delta M t/\hbar \sim 1$ (i.e., presumably $t \sim \tau_1$ according to the foregoing) might perhaps be observable under suitable circumstances. (In particular it would be required to have a very thin target A.) We are indebted to R. Serber for drawing our attention to this effect. However, we shall for the present be interested in what happens at times large compared to τ_1 where we may ignore the oscillatory term.

Suppose now that plate B is at a distance from A such that the time of flight t_f from A to B satisfies $\tau_2 \gg t_f \gg \tau_1$. This should be possible if our assumption $\tau_2 \gg \tau_1$ is correct. Then the wave function of the particles arriving at B is, practically

$$i \langle \theta_2{}^0 \rangle e^{-t_f/2\tau_2 + i\omega_2 t_f}/\sqrt{2} = \{\langle \theta^0 \rangle - \langle \bar{\theta}^0 \rangle\} e^{-t_f/2\tau_2 + i\omega_2 t_f}/2.$$

[7] For a discussion of some features of the K-particle–nucleon interactions see A. Pais and R. Serber, Phys. Rev. 99, 1551 (1955).

[8] See, e.g., R. W. Thompson in *Progress in Cosmic Ray Physics* (Interscience Publishers, Inc., New York, 1954), Vol. 3, Table 9.

In view of the difference in the absorption properties of the θ^0 and the $\bar{\theta}^0$, noted above, it should be possible to make the plate B thick enough to almost entirely remove the $\bar{\theta}^0$ part of the wave, while the θ^0 part will pass almost unattenuated (the effect of θ^0 scattering is discussed below). Thus the wave which emerges from B is, practically

$$\tfrac{1}{2}\langle\theta^0\rangle e^{i\omega t_B - t_B/2\tau_2}.$$

Hence the absorber B has restored a $\langle\theta^0\rangle$ wave of about one-forth the intensity of the original θ^0 wave emerging from A. Therefore two pion decays should reappear with a population of about one-fourth[9] the population observed near the plate A.

Apart from θ^0 absorption, a second mechanism will tend to increase the $\theta_1{}^0$ frequency beyond the block B, namely elastic scattering of either the θ^0 or the $\bar{\theta}^0$ part of the incoming wave. Such a scattering will alter the relative phase of θ^0 and $\bar{\theta}^0$ in the $\theta_2{}^0$ packet and this effect, too, will restore a $\theta_1{}^0$ component in the beam. On the other hand, charge-exchange scattering of the type (8) will tend to deplete the θ^0 component, but one can correct for this effect since the resulting θ^+ can be due only to θ^0, not to $\bar{\theta}^0$.

This rather striking prediction about the behavior of the θ^0 is in some ways similar to the behavior of polarized light under suitable circumstances. Circularly polarized light, of either sense of rotation, is a superposition of states of plane polarized light, with planes orthogonal to each other. Conversely, a plane polarized light beam either with horizontal or vertical plane of polarization, is a superposition of two circularly polarized beams with opposite sense of rotation. By selective absorption, a plane-polarized beam can thus be transformed to a circularly polarized beam and vice versa. Quite analogously, the initially produced θ^0's transform into $\theta_2{}^0$'s because of a first "absorption" (the decay of the $\theta_1{}^0$'s) and because of a second absorption (the attenuation in nuclear matter of the $\bar{\theta}^0$'s) transform back into $\theta_1{}^0$'s.

The absorption of $\bar{\theta}^0$ within the plate B must also result in the production of Λ^0 and probably of θ^- according to the reactions (5), (6), and (7). It was independently remarked by the Columbia group of Booth, Blumenfeld, Chinowsky, and Lederman[10] that the observation of Λ^0 after the absorber would also constitute a check of the time change in the composition of θ^0 as expressed in formula (9). The same group is planning an experiment to observe this effect with the Brookhaven Cosmotron.

It should be mentioned that, as the lifetime of the $\theta_1{}^0$ is relatively short, our conclusion about the reappearance of two-pion decays is verifiable most easily if B is composed of a number of parallel plates, enablin gone to observe decay events "within" the absorber.

The use of photographic plates might perhaps enable one to test another feature of the θ^0 scheme: If the absorber B is moved near the thin plate A, where the wave has not yet acquired a large $\bar{\theta}^0$ part, then θ^0, θ^-, Λ^0, $\Sigma^{+,-}$ should no longer be produced within the absorber, while θ^+ might be produced there. Since Λ^0's and θ^0's are also produced in A by the primary beam, these particles cannot be used for this second test. However, if B is made of a stack of emulsions, Σ's produced in B can be distinguished from Σ's emerging from A. Thus the second test is also within experimental feasibility, though harder to realize than the first.

Finally, the possibility should be noticed[7,11] that a beam of θ^+ might produce θ^0's by charge-exchange scattering, and similarly θ^- might produce $\bar{\theta}^0$. It is to be expected that if charge exchange occurs with a cross section of the order of 10% of the total cross section, such a production method should give a θ^0 to background ratio considerably larger than is obtained from targets bombarded by nucleons or pions.

ACKNOWLEDGMENTS

We would like to thank R. Serber and H. Snyder for stimulating discussions.

[9] Note that a normalization factor due to the difference in solid angles involved has obviously to be taken into account.

[10] Booth, Blumenfeld, Chinowsky, and Lederman (private communication).

[11] Chupp, Goldhaber, Goldhaber, Iloff, Lannutti, Pevsner, and Ritson, University of California Radiation Laboratory Report UCRL-3021, June 10, 1955 (unpublished); (two out of 18 K^+ collisions appear as probable charge-exchange scattering).