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On the Two-Meson Hypothesis*

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1. INTRODUCTION

WEISSKOPF[1] has underlined the difficulty of reconciling the high rate of production of mesons with their subsequent weak interaction with matter. He has also suggested one possible way of overcoming the apparent lack of reversibility, namely, by postulating that the primary cosmic-ray proton converts a normal nucleon in an "air" nucleus into an "excited" nucleon, capable of emitting mesons. The lifetime of the "meson-pregnant" state can be chosen sufficiently long to account for the weak interaction between mesons and nucleons. An alternative solution of the difficulty was suggested by one of the present authors (R.E.M.) at the Shelter Island Conference. The hypothesis was that two kinds of mesons exist in nature, possessing different masses: the heavy meson was supposed to be produced with large cross section in the upper atmosphere and to be responsible for nuclear forces, whereas the light meson was regarded as a decay product of the heavy meson, and as the normal meson was observed at sea level to interact weakly with matter.[2] In this note we examine briefly some of the consequences of the two-meson hypothesis.

If we postulate the existence of a heavy meson in addition to the normal (light) meson, what properties must we assign to the heavy meson on the basis of cosmic-ray evidence and of our present-day notions of nuclear forces? In particular, what can we say about its mass, its spin, and its lifetime for disintegration into a light meson? Moreover, what are the connections between various processes involving the heavy meson?

2. MASS OF THE HEAVY MESON

It is clear that if we wish to relate the mass of the heavy meson to the range of nuclear forces (in the usual field-theoretic sense), we must assume that its mass is not greater than about 350 electron masses.[3] An experimental determination of the mass and direct evidence for the existence of the heavy meson may be provided by two excellent photographs taken by Lattes, Muirhead, Occhialini, and Powell.[4] Each of these photographs (taken at 10,000 feet) shows a meson stopping in the emulsion, and a secondary meson starting with a kinetic energy of about 2 Mev. The authors suggest the very interesting interpretation that each secondary-meson track is due to the spontaneous decay of a heavy meson into a light one. On this interpretation, the difference in mass between the two mesons is about 25 Mev, provided there is only one recoil particle, i.e., one light quantum or one neutrino (see below). The implication would then be that the heavy meson has a mass of about 125 Mev and the light meson a mass[5] of 100 Mev.

It is tempting to identify the heavy and light mesons of Lattes and co-workers with the two mesons of our theory. That the two kinds of mesons cannot be identified with the components

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[1] V. F. Weisskopf, Phys. Rev. **72**, 510 (1947).

[2] This hypothesis is not to be confused with previous two-meson theories, such as the one proposed by Schwinger, in which both mesons are assumed to interact strongly with nucleons.

[3] L. E. Hoisington, S. S. Share, and G. Breit, Phys. Rev. **56**, 884 (1939).

[4] C. M. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, Nature **159**, 694 (1947). This paper arrived in the United States shortly after the two-meson hypothesis was presented at the Shelter Island Conference. Even more recently, a Russian paper (A. Alichanian, A. Alichanow, and A. Weissenberg, J. Phys. (USSR) **11**, 97 (1947)) has arrived, summarizing some cosmic-ray evidence for the existence of a particle of mass intermediate between that of the meson and the proton; however, this evidence appears less convincing than that of the British, and will not be used in our discussion.

[5] W. B. Fretter, Phys. Rev. **70**, 625 (1946), presumably measures the mass of the light meson (cf. below).

of Schwinger's mixed-meson theory, follows from the extremely short lifetime for the decay of the heavy meson into the light one predicted by the Schwinger theory.[6] Of course, many more experiments must be performed before the existence of the heavy meson and, in particular, the proposed identification can be accepted.

3. LIFETIME OF THE HEAVY MESON

An important feature of the two-meson hypothesis is the requirement that the heavy meson should have a lifetime which is sufficiently long to account for the frequency of heavy meson decays observed by Lattes and co-workers, and sufficiently short to explain the fact that at sea level and underground most mesons fail to interact strongly with nucleons (and must therefore be light mesons). We obtain an upper limit on the lifetime for the decay of a heavy meson into a light one on the basis of the meson capture, scattering, and underground-absorption experiments. A lower limit is arrived at by examining the British data in greater detail.

(a) Upper Limit

One upper limit for the heavy meson lifetime can be derived from the experiment on the capture of slow negative mesons by light atomic nuclei.[7] The negative result of this experiment implies that most of the mesons hitting the apparatus must be light mesons. If this were not the case and heavy mesons had a long enough life to survive in the atmosphere, they would suffer nuclear capture (after being stopped in the apparatus) before they could decay into light mesons. If we take 10 percent as a reasonable upper limit on the fraction of heavy mesons entering the apparatus of Conversi and co-workers, then we find $\tau_H \leqslant 1.5 \cdot 10^{-6}$ sec., where τ_H is the lifetime for the heavy meson at rest. This upper limit for τ_H is already shorter than the lifetime for the electron decay of the normal (light) meson.

A closer upper limit on the heavy meson lifetime can be obtained from the experiments on the nuclear scattering of mesons.[8] All investigators of this phenomenon have found that mesons are almost never scattered through large angles ($>20°$ or so). The cross section turns out to be less than 1 percent of the nuclear cross section. Since the primary proton has a nuclear cross section for the production of heavy mesons, the heavy meson should be scattered by nuclei with a similar cross section.[9] Hence, at sea level, at most one meson in a hundred can be heavy. Let us assume that heavy mesons with an energy greater than E survive; therefore, the fraction of heavy mesons with an energy greater than E must be less than 0.01. Now, at sea level, the fraction of mesons with an energy greater than E is $(B/B+E)^{1.8}$ ($B=2$ Bev = energy loss in atmosphere). In other words, a heavy meson must possess an energy 25 Bev before it will penetrate to sea level. If we take 20 km for the height of the meson-producing layer, we get (μ_H is the heavy meson mass)

$$(20 \text{ km}/c\tau_H) \cdot (\mu_H c^2/25 \text{ Bev}) \geqslant 1, \qquad (1)$$

or

$$\tau_H \leqslant 3 \cdot 10^{-7} \text{ sec.}$$

The closest, but not quite so certain, upper limit for the heavy meson lifetime comes from the presence of mesons deep underground. It is found[10] that mesons penetrate the equivalent of 1000 meters of water. Such mesons must possess an energy of at least $2 \cdot 10^{11}$ ev, and must be light mesons when hitting the earth. From the smoothness of the number *versus* energy curve underground[11] it follows that heavy mesons of energy up to $2 \cdot 10^{11}$ ev (and possibly more) must in general transform into light mesons before they make a nuclear collision. Since the mean free path for a nuclear collision is 1 meter of water (which is equivalent to about 10 km of air at the production level), we find:

$$(10 \text{ km}/c\tau_H) \cdot (\mu_H c^2/200 \text{ Bev}) \geqslant 1, \qquad (2)$$

or

$$\tau_H \leqslant 2 \cdot 10^{-8} \text{ sec.}$$

[6] R. J. Finkelstein (Bull. Am. Phys. Soc., Stanford Meeting, 1947) finds a lifetime of $4 \cdot 10^{-18}$ sec.

[7] M. Conversi, E. Pancini, and O. Piccioni, Phys. Rev. **71**, 209 (1947).

[8] R. P. Shutt, Phys. Rev. **69**, 261 (1946). Additional references are given in this paper.

[9] J. R. Oppenheimer (Shelter Island Conference) has pointed out that the reduction of the scattering cross section by the strong coupling theory becomes invalid at high energies (>1 Bev or so).

[10] V. C. Wilson, Phys. Rev. **55**, 6 (1939).

[11] There is a break in this curve at about 250 meters, but this is explained by the onset of radiation loss.

(b) Lower Limit

The two British tracks showing the transformation of a heavy into a light meson must be attributed to positively charged particles since a negative heavy meson must be presumed to be easily captured by a nucleus. The total number of mesons observed to stop in the plates is 65; thus the heavy mesons should be about $2\times 2/65$, i.e., 6 percent of all mesons. From the upper limit on τ_H we can say that all the heavy mesons observed must have been produced in the vicinity of the photographic plate; the slow mesons incident from the air will almost all be light mesons. If τ_H is greater than about $5\cdot 10^{-9}$ sec., then the heavy mesons may have been produced, for example, in the nearby ground (assumed 5 feet away); if $\tau_H<5\cdot 10^{-9}$ sec., only the matter in the immediate neighborhood of the photographic plate (e.g., the support of the plate) will be effective. Again, the thickness of this neighboring matter, T, must be compared with $v\tau_H$ where v is the meson velocity; the heavy mesons observable in the plate must have originated in a thickness of matter of amount T or $v\tau_H$, whichever is the smaller.

Since we are interested in the smallest value of τ_H which can account for the observed ratio of heavy to light mesons, we note that every meson when produced is heavy, but that those produced in air transform into light ones. The production rate does not change rapidly with elevation (a factor of e for 1-meter water equivalent) so that we may take it to be the same for the light and the heavy mesons which reach the plate. The ratio of observable heavy to light mesons will then depend on the energy distribution of the mesons when produced. Let us assume, for example, that this energy distribution is uniform. Then, if the light mesons stopped in the plate had kinetic energies up to E_0 at the time of their production, the heavy mesons must be able to survive whenever their kinetic energy at production is $\leqslant 0.06E_0$. The energy E_0 is about 200 Mev because for higher energies the beta-decay of the light mesons would greatly reduce their probability of reaching the photographic plate through a considerable thickness of air. Thus the heavy mesons should survive if their initial kinetic energy is less than 12 Mev. The range of such a meson would be about 1 g/cm^2; if the material were Al, this would mean 0.4 cm, and with a velocity $v\sim 10^{10}$ cm/sec., we would get $\tau_H\geqslant 4\cdot 10^{-11}$ sec. However, it is perhaps more probable that the energy distribution is given by the volume element in momentum space up to some high energy; this would increase the relative probability of faster mesons and also increase the estimated lower limit of the lifetime.

4. SPIN OF THE HEAVY MESON

No definite predictions can be made about the spin of the hypothetical heavy meson. The best qualitative theory of nuclear forces so far worked out is based on a pseudoscalar meson field with pseudovector coupling; this would indicate spin 0 for the heavy meson. For spin $\frac{1}{2}$ mesons, a theory giving the correct qualitative features of nuclear forces, and based on a meson-neutrino pair field with tensor coupling,[12] is also possible. Spin 1 mesons by themselves seem excluded.[13] However, predictions of the heavy meson spin of the basis of nuclear forces are untrustworthy in view of the essentially unsatisfactory state of all meson-field theories.

A better indication of the spin of the heavy meson can be secured from an empirical study of its decay into a light meson. If the energy of the light meson is always the same, the heavy meson decay must take place with the emission of a single recoil particle, i.e., a γ-ray or a neutrino. Neutrino or γ-ray emission could be distinguished by the absence or presence of showers associated with the decay process. If the energy of the light meson is not constant, it would follow that the decay involves the emission of at least two γ-rays or two neutrinos and that zero spin characterizes both light and heavy mesons.[14]

5. CONNECTIONS BETWEEN VARIOUS PROCESSES

According to our theory, the light meson is involved in two different processes of small prob-

[12] R. E. Marshak, Phys. Rev. **57**, 1101 (1940).

[13] See G. Wentzel, Rev. Mod. Phys. **19**, 1 (1947). Of course, it is possible that three kinds of mesons exist: two heavy mesons and one light meson (in the sense of our theory).

[14] The spin of the light meson must be 0 or $\frac{1}{2}$ from the measurements on burst production [see R. E. Lapp, Phys. Rev. **69**, 321 (1946)]. The observed bursts are produced by light mesons since energies of less than 10^{11} ev are involved and heavy mesons of this energy would decay into light mesons in the atmosphere (see Section 2(a) of this paper).

ability, *viz.* its capture by nuclei and its birth by the decay of the heavy meson. It is attractive to regard both of these processes as originating from the same fundamental interaction, and in this way[15] to explain the experiment of Conversi *et al.*[7] For the sake of a model, let us assume that the heavy meson possesses spin $\frac{1}{2}$, the light meson spin 0. Let us further assume the following direct interaction:

$$\text{Neutron}\rightarrow\text{proton}+\text{heavy meson}+\text{neutrino}, \quad (3)$$

$$\text{Heavy meson}\rightarrow\text{light meson}+\text{neutrino}. \quad (4)$$

Then the probability for the capture of a light negative meson by a nucleon can be calculated through an intermediate state, thus:

$$\text{Light meson}+\text{proton}\rightarrow\text{heavy meson}+\text{neutrino}+\text{proton}\rightarrow\text{neutron}. \quad (5)$$

Actually, the capture of a light meson can only take place in the presence of two nucleons in order to conserve momentum between the initial and final states. This is achieved in the calculation by adding another intermediate process, namely, the transfer of momentum between the two nucleons by means of the nuclear potential between them. Hence, if we calculate nuclear forces on the basis of (3), and the probability for the decay of the heavy meson on the basis of (4), we can *derive* the probability for capture of the light meson from (5).

Let us denote the strength of the coupling (3) by g. Then, if we neglect the spin and isotopic-spin dependence of nuclear forces, the interaction U between nucleons (calculated from second-order perturbation theory) is roughly:

$$U\sim(g^2/\hbar c)(E_{\max}/\mu_H c^2)^5\mu_H c^2, \quad (6)$$

over a range $(\hbar c/E_{\max})$, where $E_{\max}$ is the energy at which the intermediate states are cut off and supposedly lies somewhere between $\mu_H c^2$ and Mc^2 (M is the mass of the nucleon). The ground state of the deuteron requires the approximate constancy of the potential times the square of the range, so that:

$$(g^2/\hbar c)(E_{\max}/\mu_H c^2)^3\sim\text{const. (of order 1)}. \quad (7)$$

If we denote the strength of the coupling (4) by G, we get:

$$1/\tau_H\sim(G^2/\hbar c)(\Delta\mu/\mu_H)^2(\mu_H c^2/\hbar), \quad (8)$$

where $\Delta\mu$ is the difference in mass between the heavy and light mesons. The calculation for the meson capture leads to the formula:

$$1/\tau_c\sim 1/\tau_H(E_{\max}/Mc^2)(M/\Delta\mu)^2\times(\bar{U}/\mu_H c^2)^2(v/c), \quad (9)$$

where τ_c is the lifetime for capture (per proton) of a light negative meson inside the nucleus, $v(\sim\frac{1}{3}c)$ is the final velocity of the nucleon, $\bar{U}$ ($\sim$5 Mev) is the effective matrix element of the interaction potential between the two nucleons corresponding to the momentum transfer between them, and where we have already taken account of (7) and (8). It is seen that (9) is not too sensitive to $E_{\max}$; we put $E_{\max}\sim\mu_H c^2$.

The capture lifetime can be deduced from the the experimental result that at about[16] $Z=10$, the capture of slow negative mesons and their disintegration into electrons are about equally likely; from this $\tau_c\sim 10^{-7}$ sec. Inserting numbers into (9), we obtain: $\tau_H\sim 10^{-8}$ sec. This value can easily be in error by a factor 10 or more in view of the crudeness of the calculation (apart from the divergences which have to be cut off) and the choice of a special model. However, the fact that it falls within the range required by the cosmic-ray data at least leaves open the possibility of relating the heavy meson decay to the nuclear capture of light mesons.

Unfortunately, the present theory does not permit us to relate the normal beta-decay of nuclei to the beta-decay of the light meson. This follows from the fact that the light meson interacts so weakly with nucleons that normal beta-decay would be much too slow. Instead, it is necessary to assume that the heavy meson not only decays into a light meson, but is also capable of undergoing electron disintegration.[17] However, the lifetime of the heavy meson for electron disintegration ought to be longer than the lifetime for light meson disintegration in order to insure compatibility with the observed numbers of electrons in the cosmic radiation.[18]

[15] The possibility of such a connection was suggested independently by Lattes *et al*, reference 4.

[16] J. A. Wheeler, Phys. Rev. **71**, 320 (1947); see also E. Fermi, E. Teller, and V. Weisskopf, Phys. Rev. **71**, 314 (1947).

[17] This may be the explanation of the meson track in Fig. 3 of the paper by Lattes *et al* (reference 4) which presumably shows a heavy meson dying in the emulsion with no observable secondary track.

[18] H. A. Bethe and R. P. Feynman, Shelter Island Conference.