ON THE QUESTION OF THE EXISTENCE OF HEAVY NEUTRAL PSEUDOSCALAR MESONS

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The arguments in favor of the existence of heavy neutral pseudoscalar mesons with isotopic spin zero are discussed. A number of experiments are proposed by means of which it might be possible to settle the question of the existence of such mesons.

1. As has previously been pointed out,[1,2] in the framework of the Sakata model there can exist besides the known pseudoscalar mesons π and K two further pseudoscalar mesons* σ_1 and σ_2. Out of the nine different charge states of the system baryon + antibaryon three states ($\bar{p}p$, $\bar{n}n$, $\bar{\Lambda}\Lambda$) have identical quantum numbers and can make transitions to each other. From the diagonalization of these states there arise three other states, one with unit isotopic spin,

$$\pi^0 = (p\bar{p} - n\bar{n})/\sqrt{2},$$

and two others with zero isotopic spin,

$$\sigma_1 = \{\alpha(p\bar{p} + n\bar{n})/\sqrt{2} + \beta\Lambda\bar{\Lambda}\},$$
$$\sigma_2 = \{\beta(p\bar{p} + n\bar{n})/\sqrt{2} - \alpha\Lambda\bar{\Lambda}\}.$$

Because of the orthonormality of the states σ_1 and σ_2 the constants α and β satisfy the relation $\alpha^2 + \beta^2 = 1$. These coefficients are determined by the properties of the strong interaction between the three baryons p, n, Λ. As has been shown in a number of papers,[4-8] if the strong interactions of these baryons were identical (as they are, for example, in the model of universal vector interactions[9-11]), the Sakata model would possess an additional symmetry, which bears the name of unitary symmetry. In the framework of unitary symmetry the nine mesons break up into an octet and a singlet, and the mesons occurring in the octet (π, K, σ_1) must have equal masses; the mass of the ninth meson (σ_2) must in general be different, and may be much larger. The values of the coefficients that correspond to unitary symmetry are $\beta = (2/3)^{1/2}$, $\alpha = -(1/3)^{1/2}$. The amount of deviation from unitary symmetry in nature can be characterized by the mass difference of the K and π mesons ($\sim$ 350 Mev). This gives us reason to suppose that the mass of the σ_1^0 meson can scarcely exceed 1 Bev. At present we have no definite arguments about the mass of the σ_2^0 meson.

Considerations connected with unitary symmetry make the problem of looking for and discovering the σ meson a matter of great present interest.* In this connection we shall make a number of remarks about the possible properties of this particle.

2. The possible decays of the σ meson have been considered in the greatest detail by Zel'dovich[14] (cf. also [2]). The rapid decay $\sigma \to 2\pi$ is forbidden by parity conservation; the rapid decay $\sigma \to 3\pi$ is forbidden by the conservation of G-parity (the G-parity of σ is positive, and that of π is negative); and the decay $\sigma \to 4\pi$ must be improbable, since the π mesons are produced in states with high orbital angular momenta.

The decays into five and seven π mesons must be forbidden on account of the G-parity. Just like the decay $\sigma \to 4\pi$, the decays into six and eight π mesons will involve high orbital angular momenta, and owing to the smallness of the phase volume these decays cannot compete with $\sigma \to 4\pi$. The high orbital angular momenta in the decay $\sigma \to 4\pi$ are due to the fact that a pseudoscalar configuration of the four π mesons arises. The following 4π decays are possible:

$$\sigma \to 2\pi^+ + 2\pi^-, \qquad \sigma \to 2\pi^0 + \pi^+ + \pi^-, \qquad \sigma \to 4\pi^0.$$

The matrix element for the decay into $2\pi^+ + 2\pi^-$ is of the form

$$M = (L/\mu)^7 \varepsilon_{\alpha\beta\gamma\delta} p_{1\alpha} p_{2\beta} p_{3\gamma} p_{4\delta} (p_1 - p_2)_\mu (p_3 - p_4)_\mu \varphi_1\varphi_2\varphi_3\varphi_4\varphi_\sigma,$$

where μ is the mass of the π meson, L is a dimensionless quantity, p_1 and p_2 are the four-

*In[1,2] these mesons were denoted by ρ_1^0 and ρ_2^0. Recently, however, the letter ρ is used in the literature to denote vector mesons. We do not use the notation π^{00}, since it refers to a hypothetical σ_1^0 meson with a mass equal to that of the π meson.[3]

*Recently, on the basis of ideas about an eightfold symmetry, Gell-Mann[12] has concluded that the σ_1^0 meson may exist; he calls this particle χ^0. The conclusion that such a meson may exist has also been reached by V. M. Shekhter[13] on the basis of an analysis of the symmetries of the strong interactions.

momenta of the π^+ mesons, p_3 and p_4 those of the π^- mesons, and the φ's are wave functions. The expression for M is symmetrical under the interchanges $1 \longleftrightarrow 2$ and $3 \longleftrightarrow 4$.

In the language of orbital angular momenta the expression for M corresponds to $l' = l'' = 2$, $l = 1$, where l' and l'' are the orbital angular momenta of the π^+ and π^- pairs, and l is the orbital angular momentum of the relative motion of these pairs. For $l = l' = l'' = 0$ the quantity L/μ would be of the order of the effective dimensions of the region of strong interaction, i.e., $L \sim 1$. For $l' = l'' = 2$, $l = 1$, this quantity will be much smaller because of the centrifugal barrier $[L^7 \sim (5!!)^{-2}(3!!)^{-1} \sim 10^{-2}\text{—}10^{-3}]$. The decay into $2\pi^0 + \pi^+ + \pi^-$ is described by an analogous matrix element. Because of the complete symmetry of the system $4\pi^0$, the decay $\sigma \rightarrow 4\pi^0$ contains still higher orbital angular momenta. As V. I. Ogievetskii has shown (private communication), the matrix element for this decay is proportional to

$$\mu^{-11}\varepsilon_{\alpha\beta\gamma\delta}p_{1\alpha}p_{2\beta}p_{3\gamma}p_{4\delta}\,(p_1 - p_2)_\mu\,(p_3 - p_4)_\mu \times (p_1 - p_3)_\nu\,(p_2 - p_4)_\nu\,(p_1 - p_4)_\rho\,(p_2 - p_3)_\rho\,\varphi_1\varphi_2\varphi_3\varphi_4\varphi_\sigma.$$

Therefore the decay to $4\pi^0$ can be neglected in comparison with the other 4π decays. Calculating from M the probability of the decay $\sigma \rightarrow 2\pi^+ + 2\pi^-$, one easily gets

$$w \sim 10^{-7}\cdot L^{14}\,(\Delta/\mu)^{17/2}\mu,$$

where $\Delta = m_\sigma - 4\mu$ and the formula holds for values $\Delta \lesssim \mu$. In spite of the rapid rise of the probability with increase of m_σ (for $m_\sigma \gg 4\mu$ we have $w \sim m_\sigma^{15}$), one could think from the smallness of the coefficient in the 4π decay and from the formula for the probability of the decay $\sigma \rightarrow 2\pi + \gamma$ (see below) that the decay into 4π could be important only for $m_\sigma \gtrsim 1$ Bev. Beginning at $m_\sigma = 2m_K + \mu$, however, the following fast decays are allowed:

$$\sigma \rightarrow K^+ + K^- + \pi^0, \qquad \sigma \rightarrow K^0 + \overline{K}^0 + \pi^0,$$
$$\sigma \rightarrow K^+ + \overline{K}^0 + \pi^-, \qquad \sigma \rightarrow K^- + K^0 + \pi^+.$$

The decay $\sigma \rightarrow K^0 + \overline{K}^0 + \pi^0$ is particularly interesting. Because of the conservation of charge parity this decay must go either by the channel $2K_1^0 + \pi^0$ or by the channel $2K_2^0 + \pi^0$, and the channel $K_1^0 + K_2^0 + \pi^0$ must be forbidden. Thus pair production of K_1^0 mesons must occur in the experiment. For small Δ ($\Delta = m_\sigma - 2m_K - \mu$) the probability of this decay is given by

$$w \sim 10^{-3}L^2\Delta^2/m_\sigma \qquad (L \sim 1).$$

3. Let us now turn to decays that involve the electromagnetic interaction. Conservation of charge parity forbids the decay $\sigma \rightarrow \pi^0 + \gamma$ (this decay is also forbidden as a 0—0 transition, cf. [14]), and the decays

$$\sigma \rightarrow \pi^0 + e^+ + e^-, \qquad \sigma \rightarrow \pi^0 + \mu^+ + \mu^-, \qquad \sigma \rightarrow 2\pi^0 + \gamma$$

are forbidden in second order in the electromagnetic interaction. The decays

$$\sigma \rightarrow \pi^+ + \pi^- + \gamma, \qquad \sigma \rightarrow 2\gamma$$

are allowed. Because of gauge invariance the probability of the second of these decays must increase as m_σ^3 with increase of the mass of the σ meson. We can take as an approximate formula

$$w_{2\gamma}^{\sigma} = w_{2\gamma}^{\pi^0}(m_\sigma/\mu)^3.$$

Assuming $\tau_{\pi^0} = 10^{-16}$ sec, we see that $w_{2\gamma}^{\sigma} \sim 100$ ev for $m_\sigma = 2\mu$. In spite of its small width, however, as Ohnuki has remarked,[4] this decay would be the main one for $m_\sigma \lesssim 2\mu$. For larger values of the mass m_σ, as Zel'dovich has emphasized,[14] the predominant decay is

$$\sigma \rightarrow \pi^+ + \pi^- + \gamma.$$

The matrix element of this decay is of the form

$$eL^3\mu^{-3}A_ik_kp_{1l}p_{2m}\varepsilon_{iklm}\varphi_1\varphi_2\varphi_\sigma,$$

where e is the electric charge ($e^2 = \alpha = 1/137$); L is a dimensionless quantity ~ 1; and k, p_1, p_2 are the respective four-momenta of the photon, the π^+ meson, and the π^- meson.

The decay probability calculated with this matrix element is

$$w \sim 10^{-7}\alpha L^6\,(m_\sigma/\mu)^7\,\mu$$

for $m_\sigma \gg 2\mu$. The spectrum of the photons is of the form

$$n(\omega)\,d\omega \sim \omega^3\,(m_\sigma^2 - 2m_\sigma\omega - 4\mu^2)^{3/2}\,(m_\sigma^2 - 2m_\sigma\omega)^{-1/2}\,d\omega.$$

The heavier of the σ mesons (σ_2) can have in addition to these decays the decay $\sigma_2^0 \rightarrow \sigma_1^0 + 2\pi$, provided that $m_{\sigma_2^0} > m_{\sigma_1^0} + 2\mu$.

4. Let us now consider possible ways of detecting σ mesons, in the light of the existing experimental data. In the range $0 < m_\sigma < 1.8\mu$ a search for σ^0 in the reaction $d + d \rightarrow He^4 + \sigma^0$, which was made in Berkeley,[15] gave for the cross section for production of σ_1^0 the value $\sigma < 7 \times 10^{-32}$ cm^2 for $m_\sigma = \mu$, and $\sigma < 0.2 \times 10^{-32}$ cm^2 for $m_\sigma = 1.8\mu$ An experiment made with the accelerator in Frascati[16] gave $d\sigma/d\Omega < 6 \times 10^{-32}$ cm^2/sr for the cross section of the reaction $\gamma + p \rightarrow \sigma + p$ for a range of σ-meson masses at about 3.5μ. Experiments in Dubna [17] have not revealed any features associated with the production of σ mesons in the range of masses 270 Mev $\leq m_\sigma \leq$ 400 Mev.

Moreover, there are the following arguments against the existence of a σ meson with a mass much less than that of the K meson. Such a meson would occur in decays $K^+ \rightarrow \sigma + \pi^+$ if $m_\sigma < 350$ Mev. The production of σ mesons which decay through the channel $\sigma \rightarrow 2\gamma$ would increase the fraction of the energy carried away by neutral particles in the annihilation of antiprotons (in comparison with the experimentally measured value of $1/3$). [18] There are some possible indications against the existence of a σ meson with the decay $\sigma \rightarrow 2\gamma$ in the data from the analysis of annihilation stars for "lost mass." [19]

At present there are no experimental data contradicting the existence of a σ meson with mass larger than that of the K meson and with the decay $\sigma^0 \rightarrow \pi^+ + \pi^- + \gamma$. A search for this meson can be made either by trying to observe the hard photons arising in its decay or by analyzing reactions for its production (experiments of the types of [16,17,19]). A reaction convenient for kinematical analysis is

$$K^- + p \rightarrow \underset{\substack{\downarrow \\ p+\pi^-}}{\Lambda^0} + \underset{\substack{\downarrow \\ \pi^+ + \pi^- + \gamma}}{\sigma^0}.$$

Because of the uncertainty of the theoretical estimates, for a σ-meson mass near 1 Bev we cannot regard the decay $\sigma \rightarrow 4\pi$ as excluded. The existence of this decay is, however, improbable. The existence of a σ meson with such a decay could be detected if one were to measure the quantity $M^2 = (E_1 + E_2 + E_3 + E_4)^2 - (\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 + \mathbf{p}_4)^2$ in reactions in which $2\pi^+ + 2\pi^-$ are produced (the E's and **p**'s are the energies and momenta of these mesons).

For a sufficiently large mass of the σ meson one could look for it in the decay $\sigma \rightarrow 2K + \pi$, by studying the kinematical distribution of K mesons (in particular pairs of K_1^0 mesons) in reactions at high energies. For a pair of K mesons produced in the decay of a σ meson the energy of the pair in its center-of-mass system must lie in the range $2m_K < E_{2K} < m_\sigma - \mu$.

In conclusion it must be emphasized that if it should be shown experimentally that σ mesons do not exist, this would mean that in nature unitary symmetry is catastrophically violated.

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1 L. B. Okun', JETP **34**, 469 (1958), Soviet Phys. JETP **7**, 322 (1958).

2 L. B. Okun', Proc. Ann. Int. Conf. on High Energy Physics at CERN, 1958, p. 223.

3 A. Baldin, Nuovo cimento **8**, 569 (1958).

4 S. Ohnuki, Proc. 1960 Ann. Int. Conf. on High Energy Physics at Rochester, Univ. of Rochester, 1960, p. 843.

5 S. Ogawa, Progr. Theoret. Phys. **21**, 209 (1959).

6 Ikeda, Ogawa, and Ohnuki, Progr. Theoret. Phys. **22**, 715 (1959).

7 Y. Yamaguchi, Progr. Theoret. Phys. Suppl. **11**, 1, 37 (1959).

8 J. E. Wess, Nuovo cimento **15**, 52 (1960).

9 I. Yu. Kobzarev and L. B. Okun', JETP **41**, 499 (1961), Soviet Phys. JETP **14**, 358 (1962).

10 I. Yu. Kobzarev and L. B. Okun', JETP **41**, 1205 (1961), Soviet Phys. JETP **14**, 859 (1962).

11 I. Yu. Kobzarev and L. B. Okun', Nuclear Phys. (in press).

12 M. Gell-Mann, The Eightfold Way (preprint).

13 V. M. Shekhter, JETP **36**, 581 (1959), Soviet Phys. JETP **9**, 403 (1959).

14 Ya. B. Zel'dovich, JETP **34**, 1644 (1958), Soviet Phys. JETP **7**, 1130 (1958).

15 Booth, Chamberlain, and Rogers, Nuovo cimento **19**, 853 (1961).

16 Bernardini, Querzoli, Salvini, Silverman, and Stoppini, Nuovo cimento **14**, 268 (1959).

17 Zinov, Konin, Korenchenko, and Pontecorvo, JETP **38**, 1708 (1960), Soviet Phys. JETP **11**, 1233 (1960).

18 V. I. Gol'danskii and V. M. Maksimenko, JETP **39**, 841 (1960), Soviet Phys. JETP **12**, 584 (1961).

19 F. Solmitz, Proc. Ann. Int. Conf. on High Energy Physics at Rochester, Univ. of Rochester, 1960, p. 165.

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