[3] Basov, Krokhin, and Popov, JETP **40**, 1203 (1961), Soviet Phys. JETP **13**, 845 (1961).

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WHAT IS HEAVIER, "MUONIUM ONE" OR "MUONIUM TWO"?

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SOME years ago it was noted[1] that muonium [the atomic system $M \equiv (\mu^+ e^-)$] can spontaneously transmute in vacuum into antimuonium $\bar{M} \equiv (\mu^- e^+)$. The oscillations $M \rightleftarrows \bar{M}$ would be analogous to the transmutation $K^0 \rightleftarrows \bar{K}^0$.[2]

Recently several papers devoted to this problem have appeared in the literature.[3-6] The aim of the present paper is to emphasize that the analogy between the oscillations $M \rightleftarrows \bar{M}$ and $K^0 \rightleftarrows \bar{K}^0$ is even more complete than noted earlier in that the decay of the states which are even and odd in combined parity (i.e., under PC), viz., $M_1 = (M + \bar{M})/\sqrt{2}$ and $M_2 = (M - \bar{M})/\sqrt{2}$, proceeds via different channels, as in the case of K_1^0 and K_2^0. Here M_1 and M_2 are the muonium states which are stationary in vacuo.

Let us investigate the case where only one kind of neutrino exists and there is no direct $(\mu e)(\mu e)$ interaction.[1] One would expect this case to correspond to reality if there would hold in nature the so called "Kiev symmetry," i.e., invariance of all weak interaction processes under the substitution $\mu \to \Lambda$, $e \to n$, $\nu \to p$. If $K^0 \rightleftarrows \bar{K}^0$ oscillations exist this symmetry points to a possibility of $M \rightleftarrows \bar{M}$ oscillations. In any case the transmutation would in this case be due to the same interaction which is responsible to the decay of the free muon $\mu^+ \to e^+ + \nu + \bar{\nu}$. Naturally the question arises: in what respect do the even and odd muonium states differ? The decay channels of the odd state M_2 will be

$$e^+_{\text{fast}} + \nu + \bar{\nu} + e^-_{\text{slow}}, \quad (1)$$

$$e^-_{\text{fast}} + \nu + \bar{\nu} + e^+_{\text{slow}}, \quad (2)$$

$$\nu + \bar{\nu}. \quad (3)$$

We are considering here muonium with spin 1, since a system with spin 0 can not decay into a neutrino pair in view of the neutrino helicity. The even system M_1, also with spin 1, can decay via channels (1) and (2) but the decay via channel (3) is forbidden. The circumstance that the spin-1 even system can not decay into the pair $\nu + \bar{\nu}$ is similar to the case of spin-0 odd K_2^0 meson which can not decay into two π mesons. By means of Lehman's theorem[8] one can show that the mass of M_2 is greater than that of M_1. As is well known, one cannot decide the question of which is heavier, the K_1^0 or the K_2^0 meson, on theoretical grounds,[3] because of the difficulties associated with the strong interactions.

In contrast to the $K_1^0 - K_2^0$ case, the difference in the decay characteristics of the systems M_1 and M_2 is rather small. Physically this is associated with the large size of the atomic system: even though strictly speaking the decaying objects are M_1 and M_2, in the overwhelming number of cases it is the "free" muon which decays in the atomic system. In principle, however a difference still exists between the decay channels of M_1 and M_2. It was thought worthwhile to point this out even if only for pedagogic reasons.

The above arguments about the difference in the decay channels of M_1 and M_2 remain true also if there exists a direct $(\mu e)(\mu e)$ interaction.[1] However, then the mass difference obviously will be determined by the $(\mu e)(\mu e)$ interaction[10] and we then will not be able to say anything about the sign of the mass difference of M_1 and M_2.

We now assume that there exist in nature two neutrino types: ν_e and ν_μ.[11] If e and ν_e on the one hand and μ and ν_μ on the other hand have different additive quantum numbers (charges) then the transition $M \rightleftarrows \bar{M}$ is strictly forbidden and it makes no physical sense to talk about M_1 and M_2.

We now shall discuss the recently proposed[12,13] possibility that there might exist multiplicative quantum numbers. In that case the decay of the free meson is given by

$$\mu^+ \to \begin{cases} e^+ + \nu_e + \bar{\nu}_\mu \\ e^+ + \bar{\nu}_e + \nu_\mu \end{cases},$$

and the transmutation $M \rightleftarrows \bar{M}$ is due to the direct $(\mu e)(\mu e)$ interaction. Then there does not exist a difference in the decay channels of the even and odd muonium states. Both M_1 and M_2 can decay through the channels

$$e^+_{\text{fast}} + \nu_e + \bar{\nu}_\mu + e^-_{\text{slow}}, \quad e^-_{\text{fast}} + \nu_e + \bar{\nu}_\mu + e^+_{\text{slow}}$$

$$e^+_{\text{fast}} + \bar{\nu}_e + \nu_\mu + e^-_{\text{slow}}, \quad e^-_{\text{fast}} + \bar{\nu}_e + \mu_\mu + e^+_{\text{slow}}$$

$$\nu_e + \bar{\nu}_\mu, \quad \nu_e + \nu_\mu.$$

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[1] B. Pontecorvo, JETP **33**, 549 (1957), Soviet Phys. JETP **6**, 431 (1958).
[2] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955).
[3] S. Weinberg and G. Feinberg, Phys. Rev. Lett., in press.
[4] N. Gabbibo and R. Gatto, Nuovo cimento **19**, 612 (1961).
[5] S. L. Glashow, Phys. Rev. Lett. **6**, 196 (1961).
[6] S. L. Glashow, Nuovo cimento **20**, 591 (1961).
[7] Gamba, Marshak, and Okubo, Proc. Nat. Acad. Sci. **45**, 881 (1959).
[8] H. Lehmann, Nuovo cimento **11**, 342 (1954).
[9] I. Yu. Kobzarev and L. B. Okun', JETP **39**, 605 (1960), Soviet Phys. JETP **12**, 426 (1961).
[10] L. B. Okun' and B. Pontecorvo, JETP **32**, 1587 (1957), Soviet Phys. JETP **5**, 1297 (1957).
[11] B. Pontecorvo, JETP **37**, 1751 (1959), Soviet Phys. JETP **10**, 1236 (1960).
[12] R. Gatto, Proc. 1960 Ann. Int. Conf. High Energy Phys., Rochester, Un. of Rochester (1960), p. 609.
[13] G. Feinberg and S. Weinberg, Phys. Rev. Lett. **6**, 381 (1961).

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