Remarks on the Possible Existence of a Neutral Muon (*).

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Summary. — The arguments for and against the existence of a neutral muon are discussed. The weak interactions in which a neutral muon might replace the neutrino are enumerated. It is concluded that the most favorable experimental circumstances, for the detection of the neutral muon would obtain if one searches for the reaction $K^+ \to \mu^+ + \mu^0$.

With the exception of the charged muon, all the charged fermions which have been observed in nature appear to have neutral counterparts with masses differing only by several electron masses. This is certainly true of the proton and the $\Sigma^{\pm}$ hyperon and the indirect evidence is strong for the existence of a neutral counterpart to the Ξ^- hyperon. The above statement also holds for the electron if the neutrino is regarded as the neutral conterpart of the electron although it is possible that the neutrino occupies a privileged position (cf. below). On the other hand, no evidence of any sort has been found for a neutral counterpart of the charged muon, namely a neutral particle with spin $\frac{1}{2}$, mass close to $207\, m_e$ and extremely weak interaction with matter (i.e. cross-sections comparable to those for the neutrino). Such a hypothetical neutral muon should not possess a measurable anomalous magnetic moment and consequently should possess a mass slightly less than that of the charged muon [1].

We wish to discuss briefly the conditions under which the existence of a neutral muon might be established. Since, in many ways, a neutral muon would have the properties of a heavy neutrino, a good starting point is to

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(1) Cfr. R. FEYNMAN and G. SPEISMAN: *Phys. Rev.*, **94**, 500 (1954).

consider the reactions which involve neutrinos, namely:

(1*a*) $\pi^+ \to \mu^+ + \nu$

(1*b*) $n \to p + e^- + \bar{\nu}$

(1*c*) $\mu^+ \to e^+ + \nu + \bar{\nu}$

(1*d*) $\mu^- + p \to n + \nu$

(1*e*) $K^+ \to \mu^+ + \nu$

(1*f*) $K^+ \to e^+ + \nu + \pi^0$

(1*g*) $K^+ \to \mu^+ + \nu + \pi^0$.

From a phenomenological point of view, it is plausible to allow all reactions in which the replacement of a neutral muon for a neutrino is consistent with energy conservation. Hence the allowed neutral muon reactions would be:

(1*c'*) $\mu^+ \to e^+ + \mu^0 + \bar{\nu}$

(1*d'*) $\mu^- + p \to n + \mu^0$

(1*e'*) $K^+ \to \mu^+ + \mu^0$

(1*f'*) $K^+ \to e^+ + \mu^0 + \pi^0$

(1*g'*) $K^+ \to \mu^+ + \mu^0 + \pi^0$.

If we estimate the mass difference between the charged and neutral muons by the method of Feynman and Speisman (1), we obtain $m(\mu^+) - m(\mu^0) \cong 0.13\ m_e$ and reaction (1*c'*) would be forbidden. Reaction (1*d'*) would be extremely difficult to detect because it would have to be distinguished from reaction (1*d*) which already leaves the residual nucleus in a state of low excitation energy (2).

The three K-meson reactions (1*e'*)–(1*g'*), are all possible candidates but the most promising is certainly reaction (1*e'*). The observable difference between reaction (1*e'*) and (1*e*) is that the charged muon in reaction (1*e'*) should have a kinetic energy 142 MeV (3) as compared to 152 MeV in reaction (1*e*). Reactions (1*f'*) and (1*g'*) would yield different energy spectra for the charged particles which are observed in reactions (1*f*) and (1*g*) respectively but, apart from the fact that the latter two reactions occur less frequently than reaction (1*e*), the differences in energy spectra would be much more difficult to detect.

(2) Cfr. R. E. Marshak: *Meson Physics* (New York, 1952), chap. V.
(3) Assuming that $m(\mu^0) \cong 207\ m_e$.

If we assume that the neutral muon really behaves like a heavy neutrino, i.e. that it has the same coupling strength as the neutrino, reactions (1e′) and (1e) should be equally probable. Therefore, it should be possible to decide experimentally whether reaction (1e') takes place. Surprisingly enough, the available experimental data do not rule out this reaction because the measurements of the kinetic energy of the charged muon from the $K_{\mu 2}$ decay have not been sufficiently accurate until now (4). It would be most desirable to perform a careful measurement of the energy spectrum of the charged muons from K-meson decays to ascertain whether there is any evidente for a discrete line at 142 MeV.

One may next inquire whether there are any theoretical arguments against the existence of the neutral muon. We have already remarked that the neutrino may be in a privileged position; if the mass of the neutrino is identically zero (5), the electron as well as the charged muon may be charged fermions without their neutral counterparts (in contrast to the charged baryons). It is difficult to assess this argument at the present time. Another argument against the existence of the neutral muon may be taken from the failure to observe the reactions $\pi^+ \to e^+ + \nu$ and $K^+ \to e^+ + \nu$. From our phenomenological point of view the absence of the last two reactions implies the absence of the corresponding reactions involving neutral muons, namely: $\pi^+ \to e^+ + \mu^0$ and $K^+ \to e^+ + \mu^0$. However, if one argues that the extremely small probability for the electron decay modes of the pion and of the kaon is due to the axial vector part of the weak four-fermion interactions (np; eν) and (Λp; eν) superimposed on the strong boson-fermion interactions (π; pn) and (K; pΛ) respectively (6), then one is in trouble with the neutral muon. That is to say, the axial vector interaction no longer suppresses the electron decay modes of the pion and of the kaon when the neutral muon replaces the neutrino. This follows simply from the fact that the axial vector interaction leads to a transition probability w proportional to $(m_\Lambda + m_B)^2$, where m_Λ and m_B are the masses of the two final decay particles. Hence, one would predict that $w(\pi^+ \to e^+ + \mu^0) \cong w(\pi^+ \to \mu^+ + \nu)$ and similarly for the electron decay of the kaon. These predictions are unaltered by allowing for parity break-down in the four-fermion interaction and are definitely contrary to experiment.

It would therefore appear that there are theoretical arguments against the existence of the neutral muon. However, it must be borne in mind that the axial vector explanation for the suppression of the electron decay modes of

(4) We are indebted to Professor M. F. Kaplon for checking over the experimental material on this point.

(5) Cfr. A. Salam: *Nuovo Cimento*, 5, 299 (1957); also T. D. Lee and C. N. Yang: *Phys. Rev.*, **105**, 1671 (1957); L. Landau: *Žurn. Èxp. Theor. Fiz.*, 3?, 405 (1957).

(6) We are assuming here that the kaon behaves as a pseudoscalar particle in strong interactions.

the pion and kaon compared to the muon modes is not well established. Indeed, a recent analysis of all the weak particle decays (including all the parity breakdown experiments) indicates that it is difficult to explain *all* weak decays on the basis of a superposition of a universal weak four-fermion interaction on the strong boson-fermion interaction (7). In particular, while there is evidence for axial vector coupling of the ($\mu\nu$) fermion pair to the (np) and (Λp) fermion pairs, there is evidence against such coupling of the (eν) fermion pair. This discrepancy in the behaviour of the ($\mu\nu$) and (eν) fermion pairs opens up the possibility of a difference in the behaviour of the hypothesized ($\mu\mu^0$) and (eμ^0) fermion pairs and therefore leaves open the theoretical question as to whether the neutral muon exists or not.

It hardly pays to speculate further concerning the properties of the neutral muon without some positive evidence for its existence. Reaction ($1e'$) is suggested as the most favorable for experimental investigation.

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(7) E. C. G. SUDARSHAN and R. E. MARSHAK: *Proceedings of the Padua-Venice, Conference* (1957).

RIASSUNTO (*)

Si discutono gli argomenti pro e contro l'esistenza di un muone neutro. Si enumerano le interazioni deboli in cui un muone neutro potrebbe sostituire il neutrino. Si conclude che le più favorevoli condizioni sperimentali per la rivelazione del muone neutro si otterrebbero ricercando la reazione $K^+ \to \mu^+ + \mu^0$.

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