Possible nature of direct leptons

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We discuss the role that may be played by heavy leptons that enter in vector-like schemes when direct leptons are produced and in e^+e^- annihilation. The characteristic phenomena that make it possible to verify the existence of heavy neutral leptons are indicated.

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The e^+e^- annihilation points[1,2] to the existence of charged leptons with mass 1.6—2 GeV, which apparently are not produced in neutrino experiments.[3,4] 1) It is possible that this is connected with a new lepton number, but variants based on vector-like models of weak interactions[5,6] are more attractive. These variants contain not only charged but also neutral heavy leptons, which enter in the Lagrangian paired with an electron or a muon. For example, in the six-lepton model[6,7] the weak charged lepton currents are constructed from the doublets

$$\begin{pmatrix} \nu_e & N_M & \nu_\mu \\ e^- & M^- & \mu^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_e & N_M & N_\mu \\ M^- & e^- & \mu^- \end{pmatrix}_R, \tag{1}$$

where M^- and N_M are a charged and a neutral heavy lepton with the electron number, and N_μ is a heavy Majorana fermion, which violates the muon number. The subscripts L and R correspond to $V-A$ and $V+A$ currents. The neutral currents are diagonal in this model.

We shall discuss the possible manifestations of the contribution of heavy neutral leptons in various experiments, primarily in the problem of direct leptons in hadronic reactions[8] as well as in e^+e^- annihilation.

1. *Direct leptons with large* $p_\perp$. One of the sources of direct leptons, as is well known, may be weak decays of certain still unknown mesons, containing heavy quarks Q and light quarks $q=u,d,s$ (we shall assume them to be pseudoscalar). When selecting leptons with large $p_\perp$ kinematically, the role of two-particle meson decays becomes large. It is possible even to assume that decays into $\mu\nu$ predominate in this case.[9] But then the yield of direct electrons in this kinematic region, which is experimentally close to the yield of μ,[8] should be described by an entirely different mechanism.

There is another possibility. The existence of N_M and N generates new two-particle channels for the decay of heavy mesons $F^\pm$ (as $m_F > m_N$)

$$F^+ \to \begin{cases} e^+ + N_M \\ \mu^+ + N_\mu \end{cases} \tag{2}$$

In the scheme where the quark Q has charm,[10] this is precisely how the $F^\pm$ mesons ($c\bar{s}$ or $\bar{c}s$) decay. Analogous decays of $D^\pm$ mesons ($c\bar{d}$ or $\bar{c}d$) are suppressed by the factor $\sin^2\theta_c \simeq 0.06$.

Neglecting the electron and muon masses e and μ we have

$$\frac{\Gamma(F\to lN)}{\Gamma(F\to\mu\nu)} = \frac{m_N^2}{m_\mu^2}\,\frac{(1-m_N^2/m_F^2)^2}{(1-m_\mu^2/m_F^2)^2} \approx 60 \tag{3}$$

at $m_F \sim 2$ GeV and $m_N \sim 1.2$ GeV (the choice of the value of m_N will be discussed later on). Taking for the sake of argument a scheme with a charmed quark and assuming that the quark wave function at zero depends only on the reduced mass of the quark pair we have at $m_s/m_u \approx 3/2$ and $m_c/m_u \approx 5$

$$\frac{\Gamma(F\to\mu\nu)}{\Gamma(K\to\mu\nu)} \approx \operatorname{ctg}^2\theta_c \left|\frac{\phi_F(0)}{\phi_K(0)}\right|^2 \approx \operatorname{ctg}^2\theta_c\left(\frac{m_c m_s}{m_c+m_s}\,\frac{m_s+m_u}{m_s m_u}\right)^3 \approx 110. \tag{4}$$

Substituting $\Gamma(K\to\mu\nu) \approx 5\cdot 10^7$ sec^{-1},[11] we obtain $\Gamma(F\to lN) \approx 3\times 10^{11}$ sec^{-1}, whereas for semileptonic decays we have $\Gamma(F\to\mu(e)\nu+\cdots) \approx 10^{11}$—$10^{12}$ sec^{-1}.[12] These rough estimates show that the decays (2) should be singificant and can become the main source of direct leptons at large $p_\perp$. In this approach the yields of e and μ are close if the N_M and N_μ masses are close. Decays of the type (2) lead to the following characteristic phenomena:

a) The polarization of the direct leptons depends on $p_\perp$. At large $p_\perp$ an important role is played by the decays (2), which produce left-polarized e^+ and μ^+, as in the $\pi^+\to\mu^+\nu$ decay. With decreasing $p_\perp$, the fraction of the semileptonic decays (right-polarized e^+ and μ^+) and of electromagnetic processes (unpolarized l^+l^- pairs) increases. Experiment points to left-hand polarization of μ^+ at $p_\perp \sim 2$ GeV/c[13] and to absence of polarization, in the mean, at $p_\perp \lesssim 2$ GeV/c.[14]

b) The decay of N_M (or N) generates in addition at least one charged lepton, for example, $N_M \to e^- + \text{had}$. One can therefore expect in events containing a direct lepton with large $p_\perp$ to have at least one more slow lepton. We note the characteristic property of the model (1). Since N_μ is a Majorana lepton, the cascade $F^+ \to N_\mu + \mu^+$, $N_\mu \to \mu^\pm + \cdots$ yields $\mu^+\mu^-$ and $\mu^+\mu^+$ pairs with equal probability. In models without a Majorama particle, for example in the eight-lepton model,[7] only $\mu^+\mu^-$ pairs are produced.

c) Direct leptons from the decays (2) should have energy thresholds. It appears that an analogous threshold exists also for muons with large $p_\perp$.[15] The energy dependence at small $p_\perp$ can be different.

2. ***e^+e^- annihilation.*** In the scheme (1), anomalous e events[1] are caused by production of an M^+M^- pair ($m_M \sim 1.8$ GeV) followed by a decay of the type

$$M^- \begin{cases} \nearrow \ \nu_{eR} + e^- + \bar{\nu}_e \\ \searrow \ \nu_{eR} + \mu^- + \bar{\nu}_\mu \,. \end{cases} \qquad (5)$$

The absence of γ quanta from the decay $M^- \to e^-\gamma$ limits m_N.[16] Taking into account the new data of[17] we have $m_N \lesssim 4$ GeV. If $m_N < m_M$, then decays with formation of N_M or N_μ are possible, for example $M^- \to N_M + e^- + \bar{\nu}_e$, $M^- \to N_M + \pi^-$. They lead to lepton and hadron accompaniments of the $e\mu$ events, which have not been observed as yet.[1,17] The absence of this accompaniment can be easily explained if the difference $m_M - m_N$ is not too large. Then the probabilities of the decays

$$\Gamma(M^- \to N_M + e^- + \nu_e) \approx \frac{G^2}{15\pi^3}\left(\frac{m_M^2 - m_N^2}{2m_M}\right)^5, \qquad (6)$$

$$\Gamma(M \to N\pi) \approx \frac{G^2 f_\pi^2 m_M^3}{16\pi}\left(1 - \frac{m_N^2}{m_M^2}\right)^3 \qquad (7)$$

are small, and the small momentum of the produced e and μ limits further the registration of such events.[1] It appears that at $m_N \gtrsim 1.2$ GeV the heavy neutral leptons make practically no contribution to the observed $e\mu$ events. However, their production in mesons decays can influence the multiplicity and the energy crisis in $e^+e^- \to \text{had}$.

We have used for estimates concrete models for both leptons and quarks. But the discussed questions remain also in other models.

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