Predicted properties of a superheavy lepton

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The basic properties of the decays of a superheavy, sequential lepton $L^\pm$ are examined. Special attention is focused on the multiplicity distribution in semihadronic decays of $L^\pm$. A comparison of the theoretical predictions with the experiment makes it possible to rule out the existence of such a lepton with $m_L \lesssim 13$ GeV in the investigated energy region.

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1. One of the important questions a future unified theory of elementary-particle interactions must answer is that of the number of fundamental fermions—quarks and leptons. The Glashow-Weinberg-Salam theory,[1] which requires the same number of quark and lepton doublets, gives some information about this. The well-studied doublets are naturally combined into groups (generations), each containing one doublet of leptons and quarks, of which the lightest species in each generation are leptons. If we assume that this is a systematic feature, then the discovery of a new, charged lepton (and the neutrino associated with it) must be an indication of the discovery of a new quark doublet. This occurred with the τ lepton, whose discovery[2] stimulated a search for and discovery[3] of the b quark and a continuing search for its partner, the t quark. The current theoretical concepts do not rule out the existence of heavier generations of fermions.[1] A search for them should start with the study of leptons that are heavier than the τ lepton.

We discuss the basic properties of the decays of such a superheavy lepton $L^\pm$ and the characteristic features of its production. As will be shown below, a comparison of the theoretical predictions with the available experimental data makes it possible to rule out the existence of $L^\pm$ in a broad range of masses m_L.

2. As the investigation of a τ lepton has shown,[2] an examination of the elementary decays $L^- \to \nu_L W^-$ with a subsequent transformation of the virtual boson W^- into a pair of leptons $e\bar{\nu}_e$, $\mu\bar{\nu}_\mu$, and $\tau\bar{\nu}_\tau$ or colored quarks $d\bar{u}$, $s\bar{c}$, and $b\bar{t}$ is a good approximation. The decay into bt is impossible in the $\sim$3-to $\sim$25-GeV range of masses m_L of current interest, and the remaining nine (with allowance for color) channels can be assumed to be approximately equally probable. Thus, we obtain $B_e = B_\mu \approx B_\tau \approx 1/9$ for the probabilities of purely leptonic decays. The pair of neutrinos in these decays carries away an average energy of $\sim {}^2/_3 E_L$, which is almost unobservable. In the final state the neutrinos $\nu_L \tau^- \bar{\nu}_\tau$ from the τ decay further increase the apparent energy loss.

The "direct" semihadronic decays have a probability $B_h \approx 2/3$. The neutrino in these decays carries away an energy of $\sim 1/3E_L$. Taking into account the emission of gluons by quarks (or the formation of hadrons) apparently increases the fraction of semihadronic decays[7] to some extent and decreases the energy loss, but we ignore these effects in first approximation. We note that hadrons are produced not only in direct $L^{\pm}$ decays but also because of decays of the daughter τ lepton.

3. An important characteristic of $L^{\pm}$ decays is the number of charged particles produced in them. Because of the $L^{-} \to \nu_L + (e^{-}\bar{\nu}_e, \mu^{-}\bar{\nu}_\mu, \tau^{-}\bar{\nu}_\tau)$ processes, $\sim 30\%$ of all the decays have $n_{ch} = 1$, and $n_{ch} = 3$ in 2–3% of the decays. The final states with $n_{ch} > 1$ occur primarily in the semihadronic decays. Their multiplicity can be estimated from a comparison with the e^+e^- annihilation into hadrons by assuming that the creation of hadrons in direct $L^{\pm}$ decays is similar to their creation in the e^+e^- annihilation at $E_{\text{c.m.}} \sim (2/3)m_L$.

We can use the following relation at intermediate energies for the multiplicity distribution n_{ch} of the annihilation events[8]:

$$w_{ee}(n_{ch}) = P(\tilde{n}_{ee}),$$

$$P(n) \equiv \frac{\bar{n}^n}{n!} e^{-\bar{n}}, \quad \tilde{n}_{ee} = \frac{1}{2} n_{ch} - 1. \tag{1}$$

This relation describes well a large fraction of the two-track events and their relatively slow reduction with energy, which has the following simple meaning. Because of the quantum numbers, the one-photon annihilation cannot produce the final state without charged particles. If the presence of one pair is assumed to be mandatory, and the emission of other pairs is statistically independent, then we obtain a Poisson distribution (1) of the number of additional pairs. Using the same approach to the $L^{\pm}$ hadronic decays, we obtain

$$w_L(n_{ch}) = P(\tilde{n}_L), \quad \tilde{n}_L = \frac{n_{ch} - 1}{2}. \tag{2}$$

In this case we must assume that

$$\bar{n}^h_L + 1 \approx \bar{n}^h_{ee}\Big|_{E_{\text{c.m.}} = \frac{2}{3} m_L}, \tag{3}$$

where $\bar{n}^h_L$ and $\bar{n}^h_{ee}$ are the average multiplicities of charged hadrons in the direct $L^{\pm}$ decays and in the e^+e^- annihilation.

As the energy increases, the role of cascade decays can be expected to increase, in particular, because of the production of particles with heavy quarks. The pairs cease to be independent, and the distribution is narrower than in (1). This prediction is in agreement with the data at $E_{\text{c.m.}} = 9.4$ GeV.[9]

Here, another approach is possible. The data of Ref. 9 are in agreement with the Koba-Nielsen-Olesen (KNO) scaling[10] from $E_{\text{c.m.}} = 9.4$ GeV to ~ 30 GeV:

$$w_{ee}(n_{ch}) = \frac{1}{\bar{n}} \psi\left(\frac{n_{ch}}{\bar{n}}\right). \tag{4}$$

By retaining Eq. (3), we can use for $w_L(n_{ch})$ the KNO distribution (4) with the $\psi(x)$

function taken from the e^+e^-annihilation.[9] We shall use below Eqs. (2) and (4) as the two alternative approaches to the multiplicity distribution in the direct $L^\pm$ hadronic decays.

4. We shall now discuss the production of superheavy leptons. We limit ourselves to the reaction

$$e^+e^- \to L^+L^-, \qquad (5)$$

which is the most suitable for the search of new leptons. It would appear that this reaction can be easily detected in the observed cross section of the process $e^+e^- \to$ hadrons. The measurement of this cross section, however, requres the use of the events that satisfy the special constraints resulting from the need to reduce the physical background and from the desire to eliminate the contribution of the $\tau^+\tau^-$pair production. A typical requirement is that the energy of the final state must exceed $(0.3–0.5)E_{\text{c.m.}}$ and that the condition $n_{ch} \geqslant 4$ must be satisfied. As the above discussion shows, such restrictions markedly decrease the contribution of the reaction (5), so that other methods of detecting it must be found. We summarize some of these methods.

1) Just as in the case of a τ lepton, we can search for anomalous $e\mu$ events. A simple combinatorial analysis shows that they account for 3–3.5% of all the events (5). They would supplement the $e\mu$ events from the $\tau^+\tau^-$pairs ($\sim$6.5% of all the events with the production of τ leptons).

2) Anomalous inclusive production of leptons [$\sim$23% of the events in (5) for the $e^\pm$ production and the same number for $\mu^\pm$], especially that accompanied by a large energy loss. Here, again, there is always a contribution from the τ leptons ($\sim$33% of the events of $e^+e^- \to \tau^+\tau^-$ for both $e^\pm$ and $\mu^\pm$) and from the other sources.

3) Highly noncollinear e^+e^-or $\mu^+\mu^-$pairs (and noncoplanar pairs with the initial beams) should be observed near the threshold of the reaction (5). There are only a few of them [$\lesssim$1% of all the events in (5) for each type of pair], but the background is also very small. The noncollinearity decreases with the distance from the threshold, and the electrodynamic background becomes more important.

4) Events of the type 1 + jet (one charged particle, principally a lepton, in one

TABLE I. Probabilities of the $m+n$-type events in the L^+L^- pair production

$\bar{n}_L^h$	3	4	5
m_L, GeV	4.5 – 5	7 – 8.5	12 – 13
B_{1+3}	0.31 (0.35)	0.22 (0.20)	0.16 (0.11)
B_{1+5}	0.13 (0.09)	0.15 (0.20)	0.14 (0.17)
B_{1+7}	0.04 ($\sim$0)	0.07 ($\sim$0)	0.10 (0.08)
B_{3+3}	0.08 (0.22)	0.06 (0.13)	0.04 (0.03)

hemisphere and a jet of charged hadrons in the other) are of special interest. Approximately 40% of the events are like those in (5), and the background should be small. A search for such events is attractive because it makes it possible to "probe" at once a broad range of masses m_L in a single experiment. A distribution of the particles in the jet makes it possible to estimate m_L from the measurements at one energy.

We shall examine this option in greater detail. The predicted probabilities of some events of the type $1+n$ are given as a function of $\bar{n}_L^h$ in Table I. The corresponding m_L vales are estimated on the basis of the relation (3). The numbers without the parentheses pretain to the distribution (2) and those in parentheses correspond to the distribution (4).

5. We now turn to the experimental data. Events of the $m+n$ type at $E_{\text{c.m.}} \sim 30\,\text{GeV}$ were investigated in Ref. 11. The goal of their experiment was to investigate the τ lepton, but their results can also be applied to the problem of a superheavy $L^{\pm}$ lepton. In this case, we have the constraints

$$B_{1+3}\sigma_{LL} < 0.17\,\sigma_{\mu\mu}, \qquad B_{1+5}\sigma_{LL} < 0.09\,\sigma_{\mu\mu}, \tag{6}$$

where $\sigma_{LL} = (1/2)v_L(3 - v_L^2)\sigma_{\mu\mu}$ is the cross section of the reaction (5). We can see from a comparison of Eq. (6) with Table I that the leptons with $m_L \lesssim 13$ GeV are excluded.[3]

Preliminary data[12] on the search for noncoplanar leptons at $E_{\text{c.m.}} \sim 30$ GeV and ~ 35 GeV were recently presented at a conference in Madison. As mentioned above, such methods are very sensitive at $m_L \sim (1/2)E_{\text{c.m.}}$. By combining the results of this search (if they are confirmed) and our analysis, we notice that there are no new leptons in the entire region of $m_L \lesssim 17$ GeV.

[1] The considerations based on cosmology indicate, however, that the number of lepton doublets does not exceed 4–6 and may be limited to the three doublets already known.[4]

[2] The theoretical problems associated with τ were discussed elsewhere.[5] The current information about it is described in Ref. 6. See also the references in Ref. 5 and 6 to the other review articles and to the original papers.

[3] An additional argument against the existence of a superheavy lepton in the experiment[11] is that the number of 3 + 3-type events ($B_{3+3}^{\text{exp}} = 0.05 \pm 0.03$) does not increase markedly as compared to that predicted for the $\tau^+\tau^-$ pairs ($B_{3+3}^{\tau} \approx 0.04$). The predicted fraction of such events for the L^+L^- pairs is given in Table I.

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