Search for New Charged Leptons Decaying into Massive Neutrinos and New Stable Charged Leptons in e^+e^- Collisions

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A search for sequential charged leptons decaying into massive neutrinos has been performed at $E_{\text{c.m.}}=56$ GeV at the KEK colliding-beam accelerator TRISTAN. We have found no evidence for the production of the charged heavy leptons for an integrated luminosity of 5.3 pb^{-1}. A search for stable charged leptons was also conducted yielding null results. A new mass limit on the charged heavy leptons was obtained as a function of the mass of the associated neutrinos.

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Three generations of quarks and leptons are known so far and it is quite important to know whether further generations exist or not. A large B^0-$\bar{B}^0$ mixing reported recently[1] has been interpreted in terms of more than three generations.[2] Therefore, the existence of new charged sequential leptons ($L^\pm$), which would be a clear indication of the new generation, is of special interest. We previously presented a 95%-confidence-level (C.L.) lower limit of 25 GeV/c^2 on the mass of the charged heavy leptons (m_L) with an assumption that the associated neutrino (ν_L) is massless.[3]

The present search was based on data taken by the VENUS detector at the KEK e^+e-collider TRISTAN at a center-of-mass energy $E_{\text{c.m.}}$ of 56 GeV corresponding to an integrated luminosity of 5.3 pb^{-1}. Two possibilities were considered here.

Case (i): $L^\pm$ would decay into a weak doublet and $\bar{\nu}_L(\nu_L)$. Effects of a possible finite neutrino mass (m_{ν_L}) were taken into account.[4] Usually, a massive neutrino is expected to decay through mixing with lighter neutrinos.

However, some theoretical models[5] on cosmology suggest that the heavy neutrino may be stable and may be a promising candidate for a weakly interacting massive particle. In the present analysis, we assumed that the ν_L are long lived and would not decay within our detector volume.

Case (ii): $L^{\pm}$ would be stable. This is possible when ν_L is heavier than $L^{\pm}$ and there is no mixing between ν_L and other neutrinos.

The description of the VENUS detector can be found in our previous publication[3] and references therein, and here we only mention the improvements of the detector since then. The liquid-argon shower detector has become operational as an end-cap calorimeter, covering the angular range of $0.80 < |\cos\theta| < 0.99$. The energy resolution was found to be 3.5% for 28-GeV Bhabha electrons. A further study of the central drift chamber (CDC) allowed us to improve the momentum resolution for charged particles to $\Delta p_t/p_t^2 = 0.8\%$, where p_t is a transverse momentum in GeV/c.

First, we describe the analysis concerning case (i). $L^{\pm}$ were assumed to be produced in pairs by e^+e^- annihilation and to decay subsequently into a weak doublet and a massive $\bar{\nu}_L(\nu_L)$ through the standard electroweak interaction. The decay branching fractions of $L^{\pm}$ were calculated with our taking into account nonvanishing m_{ν_L}.[6] For statistical reasons, only the hadronic final states, whose signatures are characterized by two acoplanar jets, were investigated.

The event-selection procedure was the same as previously reported.[3] We first selected events with at least five good tracks and the total energy deposited in the barrel calorimeter (lead glass) being greater than 3 GeV. These requirements removed $\tau^+\tau^-$ events and events due to beam-gas and beam-pipe interactions. In order to minimize the losses due to the undetected particles outside the CDC volume, the reconstructed thrust axis was required to satisfy $|\cos\theta^{\text{th}}| < 0.7$ where θ^{th} is the angle between the thrust axis and the beam axis. There remained 686 events after these criteria.

Figure 1(a) shows plots of $E_{\text{vis}}/E_{\text{c.m.}}$ for the selected 686 events (circles), and the Monte Carlo-simulated backgrounds from multihadron events (solid line) and from two-photon processes (dashed line). The visible energy, E_{vis}, was defined as the sum of the track momenta in CDC and the energies deposited in the calorimeters. Figure 1(b) displays the Monte Carlo data for the production of $L^{\pm}$ with $m_L = 27$ GeV/c^2 if we assume m_{ν_L} to be 0, 10, and 15 GeV/c^2 (solid, dashed, and dotted lines, respectively). Figure 1(b) suggests that the region $0.3 < E_{\text{vis}}/E_{\text{c.m.}} < 0.8$ be searched. These cuts effectively reduced backgrounds originating from two-photon interactions and multihadron events. The newly installed end-cap calorimeter was useful for the exact determination of E_{vis} and θ^{th} and therefore for the reduction of the background. When the difference between the m_L and m_{ν_L} is

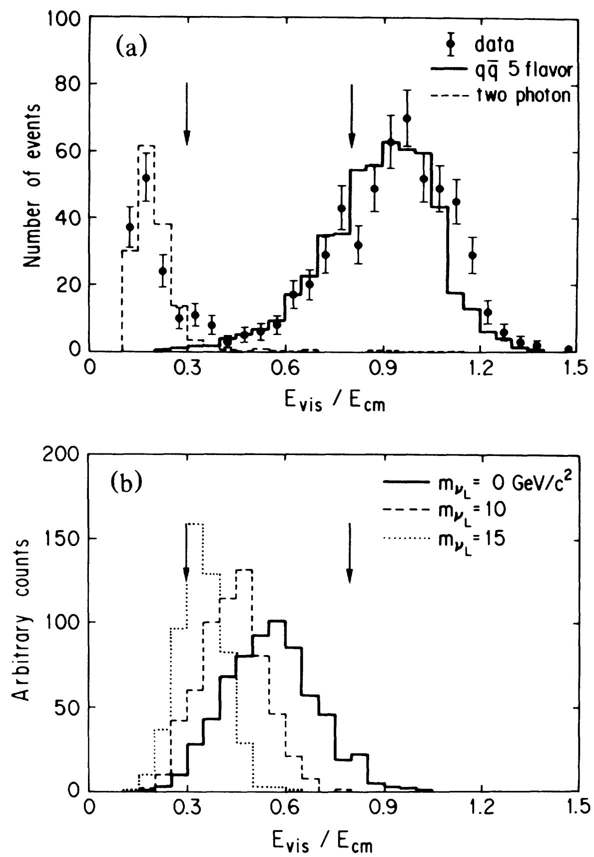

FIG. 1. Plots of $E_{\text{vis}}/E_{\text{c.m.}}$: (a) The selected 686 events and the simulated backgrounds from the multihadron events and from the two-photon processes. The backgrounds are normalized to the integrated luminosity of 5.3 pb^{-1}. (b) The production of $L^{\pm}$ ($m_L = 27$ GeV/c^2). Cuts were applied as indicated by the arrows.

less than 10 GeV/c^2, the present analysis becomes insensitive to $L^{\pm}$ production because a large fraction of the energy is carried away by $\bar{\nu}_L$ or ν_L.

The E_{vis} cuts yielded 150 events for which an acoplanarity angle distribution is displayed in Fig. 2 by circles. The acoplanarity angle is defined as

$$\cos\theta_{\text{acop}} = \frac{-(\mathbf{n}_1\times\mathbf{z})\cdot(\mathbf{n}_2\times\mathbf{z})}{(|\mathbf{n}_1\times\mathbf{z}|\,|\mathbf{n}_2\times\mathbf{z}|)},$$

where $\mathbf{n}_1$ and $\mathbf{n}_2$ are unit vectors of the momentum sum of charged tracks and energy clusters in the calorimeter in the two hemispheres separated by the plane perpendicular to the thrust axis. The unit vector $\mathbf{z}$ is parallel to the direction of the electron beam. The solid line shows the expectation from the Monte Carlo calculation for the conventional multihadron events, which reproduces our data very well. The dotted and dashed lines represent the expected yields from the $L^{\pm}$ production with $m_L = 27$ GeV/c^2 for m_{ν_L} of 0 and 15 GeV/c^2, respectively. These simulated events were normalized to the in-

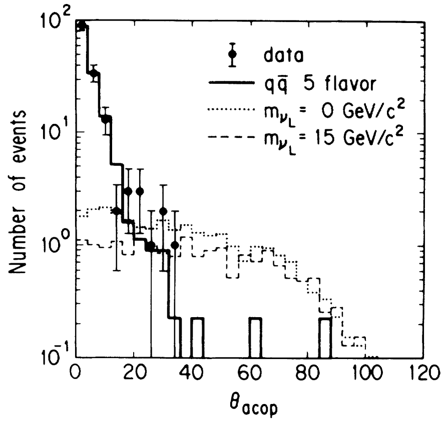

FIG. 2. A plot of the acoplanarity angle distribution for the final sample of 150 events and the Monte Carlo calculation for the multihadron events. The dotted and dashed lines represent the expected yields for the production of $L^{\pm}$ ($m_L = 27$ GeV/c^2 with $m_{\nu_L} = 0$ or 15 GeV/c^2). These simulated events were normalized to the integrated luminosity of 5.3 pb^{-1}.

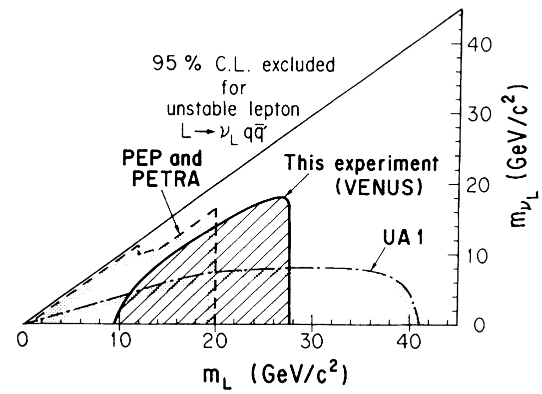

FIG. 3. A plot of the 95%-C.L. lower limits of m_L as a function of m_{ν_L}. The shaded area is excluded by the present analysis.

tegrated luminosity of 5.3 pb^{-1}. Events above 40° in the acoplanarity angle distribution were treated as candidates for $L^{\pm}$ production. There remained no events in the data. This is consistent with the 0.7 ± 0.4 event expected for the conventional multihadron events.

The acceptance for the $L^{\pm}$ production was estimated with the Monte Carlo simulation by variation of both m_L and m_{ν_L}. LUND 5.3 (Ref. 7) was used for the fragmentation of the quarks. Radiative corrections[8] up to order α^3 and the effect of Z^0 were taken into account. The systematic errors in the acceptance calculation were estimated by our taking the following into consideration: the uncertainties from the fragmentation model ($\sim 10\%$), radiative correction ($\sim 3\%$), decay branching ratio ($\leq 10\%$), cuts for the event selection ($\sim 6\%$), statistics in the Monte Carlo simulation ($\sim 10\%$), and luminosity measurement ($\sim 5\%$). The total systematic error, if these uncertainties were combined in quadrature, was 13%–21% depending on m_L or m_{ν_L}. The 95% upper limit for zero observed events was then compared with the numbers of the expected $L^{\pm}$ production for the integrated luminosity of 5.3 pb^{-1}, with the systematic error taken into account. The 95%-C.L. limits thus obtained are plotted in Fig. 3 as functions of m_L and m_{ν_L}. The results from earlier experiments are also plotted in the figure. The dash-dotted line shows the limit from UA1 experiments[9] and the dashed line shows those from experiments at the DESY and SLAC storage rings PETRA and PEP.[10]

For the case of stable $L^{\pm}$ [case (ii)], an independent study on the pair production of a heavy stable charged particle ($|Q| = 1$) was performed for the sample consisting of events with two collinear tracks. Time-of-flight (TOF) information from the TOF counter was used in this analysis. The events were selected by the following requirements:

(a) There exist only two good tracks[11] with momentum greater than 1 GeV/c. They must be oppositely charged. The positively charged particle must satisfy $|\cos\theta| < 0.7$.

(b) $\cos\theta_{\rm acol} > 0.98$, where $\theta_{\rm acol}$ is an acollinearity angle between the two tracks.

(c) The difference between T^+ and T^- must be less than 5.0 ns where $T^{\pm}$ is the TOF of the positively (negatively) charged track.

(d) The energy calculated from its momentum and velocity ($E = pc/\beta$) must exceed 5 GeV for at least one of the two tracks.

(e) Δz, the difference between the positions of the hit in the TOF counter determined by the TOF counter itself and by the track in the CDC, must be less than 18 cm in beam direction. The determination of position by the TOF counter was done with use of the time difference between the signals in a phototube at each end of the TOF counter.

Almost all multihadronic events were removed by (a), events from two-photon processes were reduced by (b) and (d), and the most serious backgrounds from cosmic rays were eliminated by (a), (c), and (e).

For the remaining sample of 1520 events, heavy (i.e., slow) charged particles were searched for in the region of $1/\beta < 1.5$. As shown in Fig. 4, no events are found there. The sensitivity of the present search was limited by the fact that the particles with $1/\beta > 6.0$ cannot be detected in the CDC or the TOF counter because their ranges are shorter than the thickness of the material inside. This corresponds to an upper bound of the mass of $m = (1-\beta^2)^{1/2} E_{\rm c.m.}/2 = 27.6$ GeV^2. We can therefore exclude at the 95% C.L. the mass range between 18.4 and 27.6 GeV/c^2 for the spin-$\frac{1}{2}$ stable charged particles.

In summary, we searched for heavy charged leptons decaying into massive neutrinos, and obtained a new limit on the mass of the charged lepton as a function of the

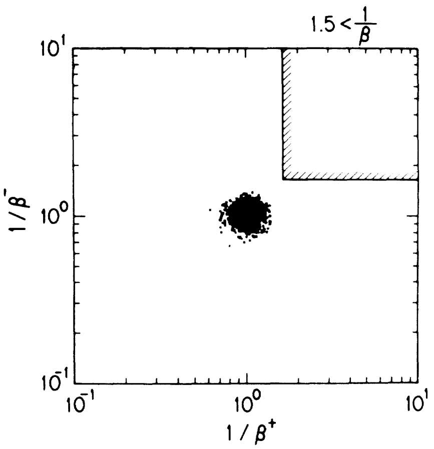

FIG. 4. A scatter plot of $1/\beta^+$ vs $1/\beta^-$, where $1/\beta^\pm$ denotes the inverse of the velocity β for the positively (negatively) charged particles. The solid lines represent the area where the stable particles were searched for.

mass of the associated neutrino. For pair production of heavy stable charged leptons, a 95%-C.L. lower limit on the mass was set at 27.6 GeV/c^2. This limit is also valid for pair production of any spin-$\frac{1}{2}$ stable charged particles such as a stable chargino.

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[1]H.Albrecht, Phys. Lett. B **192**, 245 (1987).

[2]I. I. Bigi and A. I. Sanda, Phys. Lett. B **194**, 307 (1987).

[3]H. Yoshida *et al.*, Phys. Rev. Lett. **59**, 2915 (1987).

[4]M. L. Perl, in *Proceedings of the Twenty-Third International Conference on High Energy Physics,* Berkeley, California, 1986, edited by S. C. Loken (World Scientific, Singapore, 1987), p. 596.

[5]S. Raby and G. West, Nucl. Phys. **B292**, 793 (1987); K. Enqvist, K. Kainulainen, and J. Maalampi, University of Helsinki Report No. HU-TFT-88-5, 1988 (to be published).

[6]The decay rate was calculated as

$$\Gamma(L^- \to \nu_L e^- \bar{\nu}_e) = \frac{g_e g_L m_L^5}{192\pi^3}(1 - 8y + 8y^3 - y^4 - 12y^2 \ln y),$$

where $y = m_{\nu_L}^2/m_L^2$ and g_e, g_L are coupling constants to the charged weak current and assumed to obey $g_L = g_e$ from the lepton universality. See, for example, Eq. (24) in B. C. Barish and R. Stroynowsky, Phys. Rep. **157**, 1 (1988).

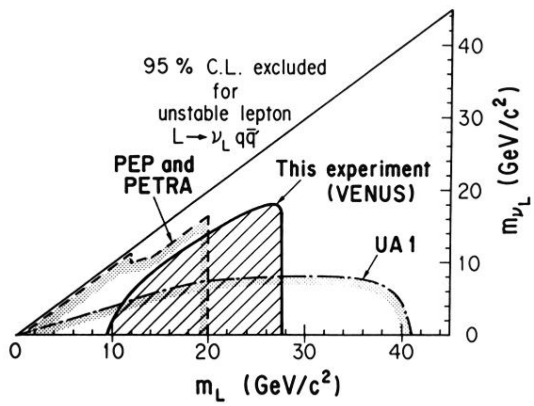
[7]B. Andersson *et al.*, Phys. Rep. **97**, 33 (1983).

[8]F. A. Berends, R. Kleiss, and S. Jadach, Nucl. Phys. **B202**, 63 (1982).

[9]R. M. Barnett and H. E. Haber, Phys. Rev. D **36**, 2042 (1987). The data analyzed in this reference were originally presented in C. Albajar *et al.*, Phys. Lett. B **185**, 241 (1987).

[10]D. P. Stoker and M. L. Perl, in *Electroweak Interactions and Unified Theories,* edited by J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, 1987); S. L. Wu, CERN Report No. CERN-EP/87-235, 1987 (unpublished), and references therein.

[11]In the analysis for case (ii), the definition of "good track" is slightly different from that for case (i) and in the previous publication. Here, the good track must have at least thirteen and six CDC hits in the r-ϕ and r-z planes, respectively, and must originate inside the cylindrical volume of 2 cm diameter $\times 5$ cm long at the interaction point.



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