Search for Unstable Heavy Neutral Leptons in e^+e^- Annihilations at $\sqrt{s}$ from 50 to 60.8 GeV

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A search for unstable heavy neutral leptons has been made at center-of-mass energies from 50 to 60.8 GeV with the AMY detector at the KEK storage ring TRISTAN. The neutral leptons are assumed to decay via mixing to electrons and muons. Events with two leptons were searched for. No evidence for their existence was found. Limits in the mass range $7.8 \le M_{L^0} \le 28.1$ GeV/c^2 and mixing-parameter range $9\times10^{-10} \le |U_{lL}|^2 \le 1$ are presented for Dirac- and Majorana-type neutrinos.

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In the three known lepton generations, the charged member has always been the first to be experimentally observed. A possible fourth-generation charged lepton has yet to be found.[1] However, the fourth generation may still be observed via the neutral lepton, assuming the neutral lepton is massive, but lighter than its charged partner, and mixes with the other lepton generations. Searches for heavy neutral leptons have been conducted at the DESY and SLAC storage rings PETRA[2,3] and PEP,[4] with negative results. Here we report on a search for unstable heavy neutral leptons that couple to electrons (muons), made with the AMY detector at the

KEK storage ring TRISTAN at $\sqrt{s}$ from 50 to 57 (60.8) GeV, with a total luminosity of 19.3 (27.4) pb^{-1}.[5] We also find no evidence for heavy neutral leptons. Limits for the cases of coupling to electrons only, coupling to muons only, and equal coupling to electrons and muons are presented for both Dirac- and Majorana-type neutrinos.

The AMY detector is a compact detector based on a 3-T solenoid magnet.[6,7] Charged particles are detected by a straw-tube inner tracking chamber (ITC) and a cylindrical central drift chamber (CDC). The CDC covers the region defined by $|\cos\theta| \leq 0.87$, where θ is measured relative to the beam axis. Between the CDC and the magnet coil is a finely segmented electromagnetic calorimeter (SHC). Outside the iron flux return are planar drift chambers and scintillation timing counters for muon identification. The details of the electron and muon identification have been described previously.[7]

Heavy neutral leptons can be pair produced through s-channel annihilation via the Z^0. The cross section for $e^+e^- \to L^0\bar{L}^0$ is

$$\sigma = \frac{G_F^2 s}{48\pi}\frac{[(1-4\sin^2\theta_W)^2+1]}{(1-s/M_Z^2)^2+\Gamma_Z^2/M_Z^2}T\,,$$

where the threshold factor $T=\beta(3+\beta^2)/4$ for Dirac-type neutrinos (L^0_{Dirac}) and $T=\beta^3$ for Majorana-type (L^0_{Majorana}), θ_W is the Weinberg-Salam electroweak angle, M_Z and Γ_Z are the mass and width of the Z^0 vector boson, and β is the velocity of the heavy neutral lepton in the center-of-mass frame. Near threshold, the cross section for L^0_{Majorana} is more strongly suppressed than the L^0_{Dirac} cross section. The cross section for either case rapidly increases as $\sqrt{s}$ approaches the Z^0 mass.

Heavy neutral leptons can also be singly produced through t-channel W exchange, $e^+e^- \to L^0\bar{\nu}_e$. The cross section for this process depends on the degree of mixing between L^0 and the electron generation. Single L^0 production is not considered in this analysis.

The decay of the L^0 is expected to proceed via mixing with a light lepton (l), analogous to the decay of a charged lepton through a virtual W boson. For Dirac neutrinos, the decay is given by

$$L^0_{\text{Dirac}} \to l^- W^+ \,\hookrightarrow\, \begin{pmatrix}\nu_e\\ e^+\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu^+\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau^+\end{pmatrix}\begin{pmatrix}u\\ \bar{d}'\end{pmatrix}\begin{pmatrix}c\\ \bar{s}'\end{pmatrix}.$$

Universality predicts the W-decay probabilities to each fermion doublet are roughly equal, giving a branching fraction of $\sim\frac{1}{9}$ to each lepton doublet and $\sim\frac{2}{3}$ to hadrons. Detailed calculations slightly modify the branching fractions.[8] For example, in the case of a Dirac neutrino with $M_{L^0}=27$ GeV/c^2,

$$B(L^0\to l^-\nu_e e^+)\sim B(L^0\to l^-\nu_\mu\mu^+)\sim 0.108B(L^0\to l^-)\,,\quad B(L^0\to l^-\nu_\tau\tau^+)\sim 0.104B(L^0\to l^-)\,,$$
$$B(L^0\to l^-u\bar{d})\sim B(L^0\to l^-c\bar{s})\sim 0.322B(L^0\to l^-)\,,\quad B(L^0\to l^-u\bar{s})\sim B(L^0\to l^-c\bar{d})\sim 0.017B(L^0\to l^-)\,,$$

where

$$B(L^0\to l^-)=\sum_{f_1,\bar{f}_2} B(L^0\to l^- f_1\bar{f}_2)\,.$$

The L^0_{Dirac} lifetime is given by

$$\tau_{L^0}=\frac{m_\mu^5}{M_{L^0}^5}\frac{\tau_\mu}{\sum_l |U_{lL}|^2}\sum_l B(L^0\to l^-\nu_e e^+)\,,$$

where $|U_{lL}|$ describes the mixing between L^0 and the l-lepton generation, and m_μ and τ_μ are the muon mass and lifetime, respectively. For Majorana neutrinos, the neutrino and its antiparticle are identical, so $L^0_{\text{Majorana}} \to l^- f_1\bar{f}_2$ and $L^0_{\text{Majorana}} \to l^+\bar{f}_1 f_2$ occur with equal rates. This doubles the decay rate, resulting in an L^0_{Majorana} lifetime equal to half the expected L^0_{Dirac} lifetime.

We consider the case where at least one of the W's decays hadronically, which should occur approximately $\frac{8}{9}$ of the time for the $L^0\bar{L}^0$ pair. In order to lower the background from two-photon and τ production processes, we do not look for the lower-multiplicity events from exclusive lepton decays of the L^0 pair. In decays of a high-mass L^0, the leptons tend to be isolated from the other decay products. Thus, the events are expected to have the following character: (i) at least two leptons; (ii) the leptons are isolated from other particles and have relatively high momenta. To ensure high trigger and track reconstruction efficiencies, the search is restricted to L^0's decaying within 5 cm of the interaction point. This places a lower limit on the sensitivity to the mixing level.

Events satisfying the following criteria were selected: (1) A total energy deposition of at least 3 GeV in the SHC. (2) At least five charged tracks, each with $|\cos\theta| \leq 0.85$. (3) Thrust ≤ 0.96. (4) At least two identified leptons: (a) For coupling to electrons, at least one of the leptons is required to be an electron; (b) for coupling to muons, both leptons are required to be muons; (c) for equal coupling to electrons and muons, the combined results of (a) and (b) are used. (5) $\alpha_i \geq 5°$ ($i=1,2$) and $\alpha_1+\alpha_2 \geq 40°$, where α_i is the angle between the ith lepton and its closest neighboring charged track. (6) The momentum of each lepton in the lepton pair is at least 3 GeV/c.

The selection efficiencies for heavy neutral leptons are calculated using Monte Carlo simulations.[9] Selection efficiencies increase with L^0 mass from $\sim$15% at $\beta=0.95$ to $\sim$41% at $\beta=0.32$ for either Dirac or Majorana L^0's coupling to electrons or muons. For equal

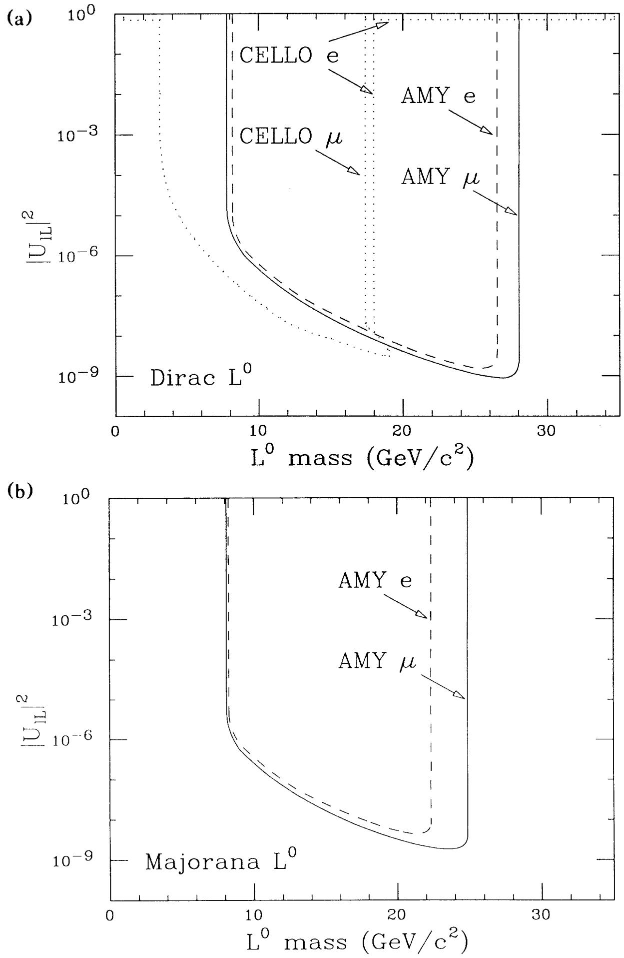

FIG. 1. Mixing parameter $|U_{lL}|^2$ vs L^0 mass excluded regions at 95% C.L. for (a) Dirac and (b) Majorana neutrinos. Dashed (solid) line gives limits for dominant coupling to electrons (muons). Dotted lines give CELLO limits (Ref. 3).

coupling [$B(L^0 \to e f_1 \bar{f}_2) = B(L^0 \to \mu f_1 \bar{f}_2) = 0.5$, $|U_{eL}|^2 = |U_{\mu L}|^2$], the corresponding efficiencies for Dirac and Majorana L^0's are ~16% to ~43% in the 50–57-GeV data sample, and ~4% to ~12% in the 57.25–60.8-GeV data sample. These efficiencies are insensitive to the location of the L^0 decay vertex within 5 cm of the interaction point. Including radiative corrections,[10] we expect to observe 6.5 (10.1) events for $M_{L^0} = 9$ GeV/c^2, and 10.1 (18.7) events for $M_{L^0} = 17$ GeV/c^2 in the 19.3 (27.4) pb^{-1} data sample for Dirac L^0's coupling to electrons (muons). For Majorana-type neutrinos, we expect 5.9 (9.3) events for $M_{L^0} = 9$ GeV/c^2, and 6.8 (12.7) events for $M_{L^0} = 17$ GeV/c^2. For Dirac L^0's with equal coupling, we expect 8.0 events for $M_{L^0} = 9$ GeV/c^2, and 13.8 events for $M_{L^0} = 17$ GeV/c^2. Corresponding values for Majorana neutrinos are 7.3–9.3 events. The number of expected events for either type of L^0 decreases to 0 as $M_{L^0} \to \sqrt{s}/2$, due to the threshold suppression in the L^0

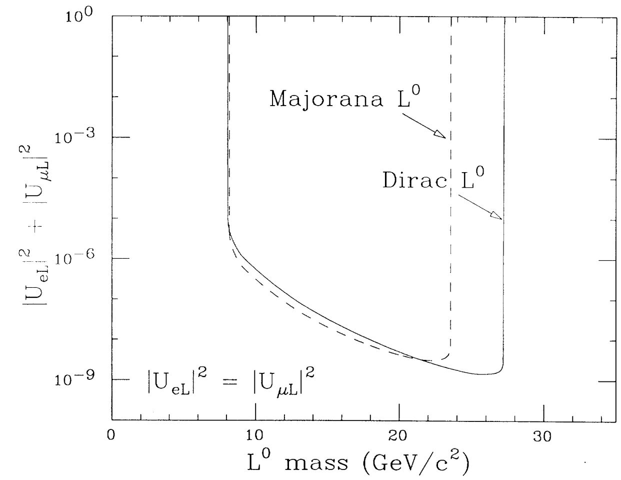

FIG. 2. Mixing parameter $|U_{eL}|^2 + |U_{\mu L}|^2$ vs L^0 mass excluded regions at 95% C.L. for $B(L^0 \to e f_1 \bar{f}_2) = B(L^0 \to \mu f_1 \bar{f}_2) = 0.5$. Solid (dashed) line gives limits for Dirac (Majorana) neutrinos.

cross section. Expected backgrounds from ordinary processes are estimated using Monte Carlo simulations for two-photon processes,[11,12] τ pair production,[9] and five-quark-flavor hadronic-annihilation processes.[12] They are estimated to be 1.06 ± 0.44 (0.89 ± 0.32) events for the electron (muon) search.

No candidate events are found in either the electron or the muon search. In evaluating our results, the following are included: (i) statistical errors in the Monte Carlo simulation (~5%); (ii) systematic errors in the Monte Carlo simulation (~6%); (iii) luminosity uncertainties (~3.4%); and (iv) trigger uncertainties (~2%). Added in quadrature, the total estimated error is ~9%, which does not depend strongly on neutral lepton mass. In obtaining the excluded mass regions at 95% C.L., we conservatively reduce the expected number of events by twice the estimated error. Assuming that the L^0's are short lived ($c\gamma\beta\tau_{L^0} \to 0$), so that all decay within 5 cm of the interaction point, 95%-C.L. excluded regions of $8.2 \le M_{L^0} \le 26.5$ GeV/c^2 for Dirac L^0's and $8.3 \le M_{L^0} \le 22.4$ GeV/c^2 for Majorana L^0's with coupling to electrons only are obtained. Corresponding limits for coupling to muons only are $7.8 \le M_{L^0} \le 28.1$ GeV/c^2 for Dirac L^0's, and $8.1 \le M_{L^0} \le 24.9$ GeV/c^2 for Majorana L^0's. Limits for equal coupling are $8.0 \le M_{L^0} \le 27.2$ GeV/c^2 for Dirac L^0's, and $8.1 \le M_{L^0} \le 23.6$ GeV/c^2 for Majorana L^0's.

Taking into account the probability for both L^0's to decay within 5 cm of the interaction point, we obtain limits on the mixing parameter $|U_{lL}|^2$ vs M_{L^0}. The excluded regions at 95% C.L. for L^0_{Dirac} coupling to electrons only and muons only are shown in Fig. 1(a). Also shown in Fig. 1(a) are the previous limits obtained by the CELLO group.[3] Our limits for L^0_{Majorana} are shown in Fig. 1(b). Limits on $|U_{eL}|^2 + |U_{\mu L}|^2$ vs M_{L^0} for equal coupling ($|U_{eL}|^2 = |U_{\mu L}|^2$) are shown in Fig. 2. Our limits extend previously published limits on $|U_{lL}|^2$ vs M_{L^0}.[2,3,4,13]

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