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Experimental limits on massive neutrinos from e^+e^- annihilations at 29 GeV

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A search was made in 29-GeV e^+e^- annihilations for massive neutrinos decaying to $e^{\pm}X^{\mp}(\nu)$ where X is a muon or meson. A 300-pb^{-1} data sample yielded just one candidate event with a mass $m_{eX} > 1.8$ GeV. Significant limits are found for new neutrinos with masses from 1.8 to 6.7 GeV and with mixing parameters in the range $3\times10^{-6} < |U|^2 < 1$.

The replication of fermion families, as exemplified by the electron, muon, and τ lepton, remains a deep puzzle of particle physics. The mass limits for neutrinos are small compared to the masses of the associated charged leptons,[1] leading to the interesting possibility that evidence for additional particle families might first appear in the neutrino sector. Indeed, massive neutrinos could provide spectacular experimental signatures in existing detectors.[2] Electron-positron annihilation is a particularly sensitive reaction for neutrino searches since the process $e^+e^-\to L^0\bar{L}^0$, mediated by a virtual Z^0, is flavor conserving and is, therefore, not constrained by small mixing parameters connecting neutrinos of different families.

We report here final results from a neutrino search carried out with the High Resolution Spectrometer (HRS) at the PEP electron-positron collider at SLAC. The data were obtained at a center-of-mass (c.m.) energy of 29 GeV and correspond to an integrated luminosity of 300 pb^{-1}. Details of the HRS are given elsewhere.[3] The spectrometer provided charged-particle tracking and electromagnetic calorimetry over 90% of the full solid angle. The detector did not identify muons. No attempt was made in this search to identify pions, kaons, and protons although a limited capability to do so existed within certain momentum intervals.

A search for massive neutrinos can be interpreted only in terms of a specific model for their production and decay. For the production we take the process $e^+e^-\to Z^0\to L^0\bar{L}^0$, where the neutrinos are assumed to have the usual $V-A$ standard-model couplings to the virtual Z^0. The differential production cross section is then given by[4]

$$\frac{d\sigma}{d\Omega}=\frac{G_F^2M_Z^4s\beta\{[(1-4\sin^2\theta_W)^2+1](1+\beta^2\cos^2\theta)+4(1-4\sin^2\theta_W)(\beta\cos\theta)\}}{256\pi^2[(s-M_Z^2)^2+M_Z^2\Gamma_Z^2]}\,, \tag{1}$$

where s is the square of the c.m. energy, θ is the neutrino production angle, and βc is the c.m. neutrino speed. Using the values $G_F=1.166\times10^{-5}$ GeV^{-2}, $M_Z=92.6$ GeV, $\Gamma_Z=2.8$ GeV, $\sin^2\theta_W=0.226$, and integrating over θ we obtain a total production cross section at $\sqrt{s}=29$ GeV of $0.36\beta(3+\beta^2)/4$ pb. This value includes a correction from initial-state radiation which lowers the cross section by 3%.[5]

The massive neutrinos are assumed to decay, in analogy with quarks, via standard-model charged currents because of unitary mixing with the known, light neutrinos. The decay properties are then completely specified by the neutrino mass and the elements of the unitary matrix U that relates the mass and weak eigenstates of the neutrinos. We assume that the mixing is dominated by one particular light neutrino and consider separately the cases $L\to eW$, $L\to\mu W$, and $L\to\tau W$, where W is the virtual, charged vector boson that couples to fermion pairs in the usual manner. The partial decay widths of the massive neutrino to various final states such as $L\to le\nu$, $l\mu\nu$, $l\tau\nu$, $l\pi$, $l\rho$, lA, and l hadron continuum, where $l=e$, μ, or τ, have been estimated with the same techniques first used in the evaluation of τ lepton decay modes.[6] The neutrino lifetime is then given in terms of its mass M and mixing parameter U_l by

$$t=\frac{192\pi^3}{G_F^2M^5|U_l|^2}f(M)\ , \qquad (2)$$

where $F(M)$ is a calculated factor that summarizes the couplings and effects of phase space associated with all possible decay channels. Lifetimes for $|U_l|^2\equiv1$ are given in Fig. 1 as a function of the L^0 neutrino mass.

The experimental signature for heavy-neutrino production chosen for this study is an event configuration with a pair of oppositely charged tracks, isolated in one hemisphere, where one track is identified in the calorimeter as an electron and the other as a nonshowering particle X so that X is not an electron. This $e^\pm X^\mp$ pair, accompanied by possible light unobservable neutrinos is a potential signature for the weak decay of a neutral particle. No strong constraint is placed on the recoiling jet of particles opposite the $e^\pm X^\mp$ pair so that the search is for the process $e^+e^-\to(L^0\to e^\pm X^\mp(\nu))$ ($\bar{L}^0\to$anything) and its charge conjugate. No attempt is made to identify the nonshowering particle $X^\mp$ because of the limited capabilities of the HRS. Preliminary results from this search, based on the initial one-third of the data, were reported previously.[7]

The following decay modes contribute to final states with the above signature.

(a) $L\to eW$:

$L^0\to e^-\mu^+\nu$, $L^0\to e^-(\pi^+ \text{ or } K^+)$,

$L^0\to e^-(\tau^+\to\mu^+\nu\nu)\nu$, $L^0\to e^-(\tau^+\to\pi^+\nu \text{ or } K^+\nu)\nu$;

(b) $L\to\mu W$:

$L^0\to\mu^-e^+\nu$, $L^0\to\mu^-(\tau^+\to e^+\nu\nu)\nu$;

(c) $L\to\tau W$:

$L^0\to(\tau^-\to e^-\nu\nu)\mu^+\nu$, $L^0\to(\tau^-\to e^-\nu\nu)(\pi^+ \text{ or } K^+)$,

$L^0\to(\tau^-\to\mu^-\nu\nu)e^+\nu$, $L^0\to(\tau^-\to\pi^-\nu \text{ or } K^-\nu)e^+\nu$,

$L^0\to(\tau^-\to e^-\nu\nu)(\tau^+\to\mu^+\nu\nu)\nu$,

$L^0\to(\tau^-\to e^-\nu\nu)(\tau^+\to\pi^+\nu \text{ or } K^+\nu)\nu$,

$L^0\to(\tau^-\to\mu^-\nu\nu)(\tau^+\to e^+\nu\nu)\nu$,

$L^0\to(\tau^-\to\pi^-\nu \text{ or } K^-\nu)(\tau^+\to e^+\nu\nu)\nu$.

The total branching ratios for $L^0\to lW\to e^\pm X^\mp(\nu)$, where $l=e$, μ, or τ, are shown in Fig. 2 as a function of L^0 mass.

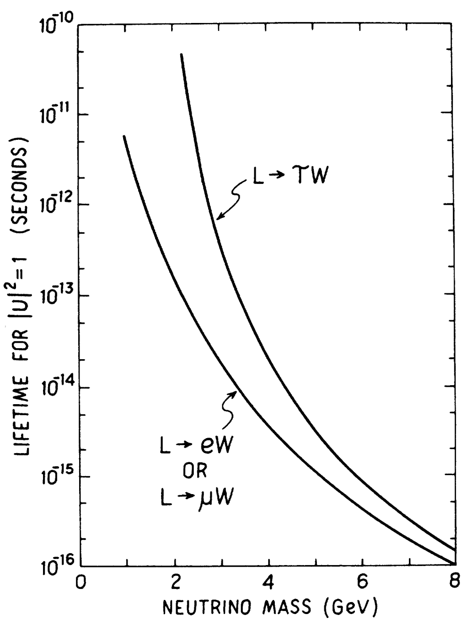

FIG. 1. Expected lifetime of massive neutrinos in the limit of complete mixing, $|U|^2=1$. The W in $L\to eW$, etc., is a virtual $W^\pm$ boson.

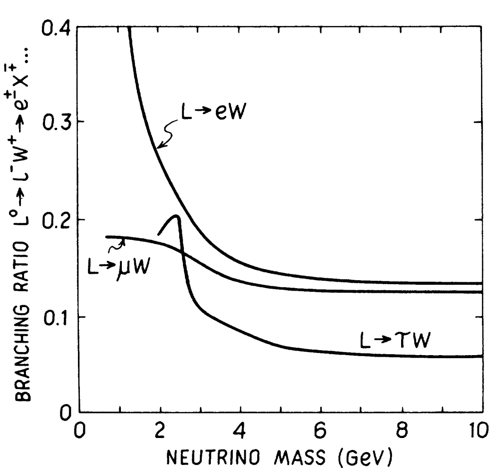

FIG. 2. Expected branching ratio for the decay of massive neutrinos into $e^\pm X^\mp$ plus possible light neutrinos, as a function of mass. The particle $X^\mp$ is a muon, pion, or kaon.

Event-selection criteria were chosen to provide good efficiency for detecting possible $e^+e^- \to L^0\bar{L}^0$ events while rejecting most known annihilation and two-photon reactions. We list the most important of these criteria with some brief comments.

Charged multiplicity. $n_{ch} \geq 4$ consistent with the assumption that the neutrinos decay via charged currents.

Kinematics. For the $e^\pm X^\mp$ pair, the magnitudes of the momenta satisfy $p_e > 1.0$, $p_X > 1.0$, and $(p_e + p_X) > 4.0$ GeV/c. This requirement was imposed for good electron identification which becomes less discriminating below 1 GeV/c. The opening angle of the pair satisfies $\cos\theta_{eX} > 0.2$ to reject random combinations from two separate jets.

Isolation of $e^\pm X^\mp$ pair. No other charged particles were allowed in the hemisphere centered on the total $e^\pm X^\mp$ pair momentum vector. No photons with $E > 0.1$ GeV were allowed within a cone of half-angle 60° centered on the pair momentum vector. A cone rather than a hemisphere requirement was made on photons since occasionally charged tracks from the recoiling jet would curl back in the 1.6-T field of the HRS towards the $e^\pm X^\mp$ hemisphere and give calorimeter signals near the boundary of the hemisphere that are difficult to interpret.

Particle identification. Electrons were identified by demanding that a calorimeter signal with energy E be spatially coincident with a charged track of momentum p such that $0.7 < E/p < 1.3$. Nonshowering particles were identified by demanding that they deposit less than 0.5 GeV in the calorimeter where 0.2 GeV is a typical value for a minimum-ionizing particle.

Twenty-seven events satisfied these analysis requirements. Four of these events were kinematically consistent with four-prong QED processes. Since none of the four events had combinations of charged-particle pair masses consistent with the hypothesis $e^+e^- \to (L^0 \to e^-\pi^+)(\bar{L}^0 \to e^+\pi^-)$, they were rejected, leaving 23 candidate events for the neutrino search. For each event, the effective mass of the $e^\pm X^\mp$ pair (m_{eX}) and that of the recoiling jet of particles (m_J) is plotted in Fig. 3. The effective masses were calculated assuming $m_e = m_X = 0$.

The candidate events are characterized by $e^\pm X^\mp$ pairs with low effective mass, with only one pair having a mass above 1.73 GeV. None of the events have an anomalous decay vertex that would be the sign of the decay of a massive, long-lived neutrino. A number of background sources are expected to yield low-mass $e^\pm X^\mp$ pairs. These include semileptonic decays of isolated charmed particles and low-multiplicity jets, where either charged pions and photons overlap to yield fake electrons or where a charged pion interacts in the calorimeter and mimics an electron. In our previous study we found that the number of observed $e^\pm X^\mp$ low-mass pairs is consistent with such backgrounds.[8] We have not made a detailed investigation of possible physical backgrounds for events with high-mass $e^\pm X^\mp$ pairs. Processes that could contribute include $e^+e^- \to e^+e^-$ hadrons, $e^+e^- \to \tau^+\tau^-$ hadrons, and production of b quarks.

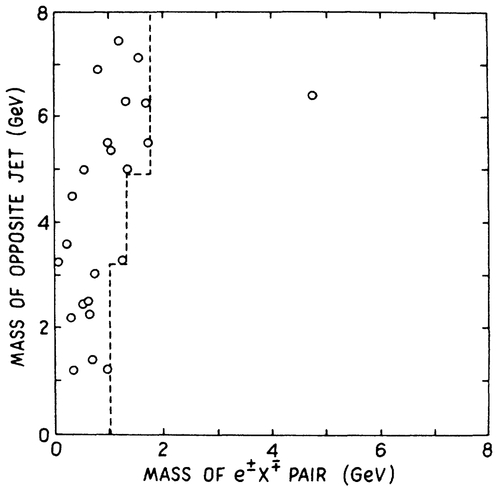

FIG. 3. Measured mass distribution for events with an isolated $e^\pm X^\mp$ pair recoiling against a jet of particles in the opposite hemisphere. The dashed line represents an empirical boundary used in setting limits on the production of massive neutrinos.

We do not make a background subtraction but, rather, set limits on the production of massive neutrinos based on the following consideration. The number of events with $m_{eX} \leq 1.73$ GeV is consistent with background. Let us assume that these are background events. The simple mass contour drawn in Fig. 3, therefore, represents an empirical boundary of the background. We then set limits on neutrino production by only searching the mass region to the right of this empirical mass contour. This search region contains either zero or one event, depending on neutrino mass. The validity of this approach to setting limits on neutrinos with mass above ~ 2 GeV is based on the following three points. First, the number of observed low-mass events is consistent with background estimates. Second, the distribution of $e^\pm X^\mp$ pair masses cuts off sharply at the mass of charmed mesons, as expected. Third, the region in the m_{eX} vs m_J

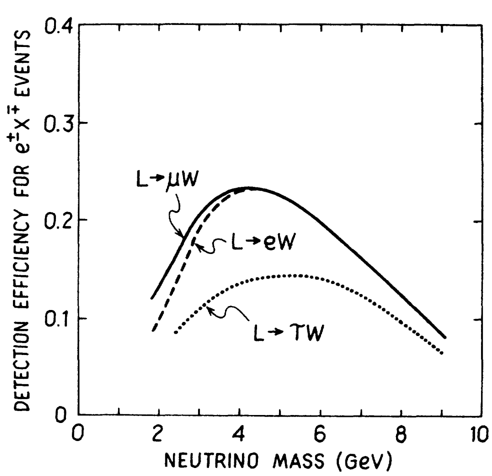

FIG. 4. Calculated detection efficiency for observing events of the type $e^+e^- \to (L^0 \to e^\pm X^\mp(\nu))$ ($\bar{L}^0 \to$anything) in the limit $|U|^2 = 1$.

space open to the neutrino search represents a major fraction of the total phase space, so that small variations in the empirical mass contour in Fig. 3 do not have a significant impact on the limits that we find, especially for neutrino masses above ~3 GeV.

The one high-mass candidate event is characterized by an e^+X^- pair with $p_e=11.2$ GeV/c, $p_X=2.5$ GeV/c, $\cos\theta_{eX}=0.59$, and $m_{eX}=4.75$ GeV. If we assume that there is a missing light neutrino with energy of 0.8 GeV, given by the difference of the beam energy and that of the e^+X^- pair, then the effective mass of this neutrino and the e^+X^- pair is kinematically constrained to lie in the range from 4.9 to 8.1 GeV. The measured effective mass of the jet opposite the e^+X^- pair is 6.39 GeV. This value includes contributions from both charged tracks and from neutral particles detected in the calorimeter. Since the reconstruction of the momentum vectors of neutral particles is not always reliable with a calorimeter of limited segmentation as in HRS, we have also calculated a lower limit on the jet mass using only the charged-particle momenta, which are well measured. The charged particles in the jet have an effective mass of 4.9 GeV and a total energy of 8.7 GeV. Assuming that the neutral particles have an energy of $14.5-8.7=5.8$ GeV, one obtains a lower bound on the total jet mass of 6.43 GeV, which is close to the measured total jet mass. In setting cross-section limits for massive neutrinos, we shall take the number of candidate events to be zero below 6.4 GeV and equal to one above this value.

Cross-section limits at a given confidence level (C.L.) and, as a function of neutrino mass M and mixing parameter $|U|^2$, are given by

$$\sigma_{\mathrm{C.L.}}(M,|U|^2)=\frac{N_{\mathrm{C.L.}}(M)}{P_{eX}(M)\epsilon(M,|U|^2)\int L\,dt}\,, \quad (3)$$

where $N_{90}(1.8<M<6.4 \text{ GeV})=2.30$ based on zero observed events, and $N_{90}(M>6.4 \text{ GeV})=3.89$ for one candidate. The integrated luminosity $\int L\,dt$ is 300 pb^{-1}. The probability $P_{eX}(M)$ for an event of the type $e^+e^-\to L^0\bar{L}^0$ to yield at least one $e^\pm X^\mp$ pair is $2B-B^2$, where B is the branching ratio for $L^0\to e^\pm X^\mp$ shown in Fig. 2. Finally, $\epsilon(M,|U|^2)$ is the detection efficiency for $e^+e^-\to L^0\bar{L}^0$ events that satisfy all selection criteria including the mass requirements on m_{eX} and m_J described above. The detection efficiencies depend on both M and $|U|^2$ since the neutrino lifetime is a function of both of these parameters.

Event detection efficiencies were calculated as a function of M and $|U|^2$ using a Monte Carlo program which generated fake events of the type $e^+e^-\to(L^0\to e^\pm X^\mp(\nu))\,(\bar{L}^0\to\text{anything})$ and its charge conjugate according to the physics assumption stated above. The program generated neutrino decays to three-lepton and pion-lepton final states with the appropriate weak decay matrix elements.[9] Other decays, involving hadrons, were generated with an algorithm based on the Lund Monte Carlo program.[10] These fake events were then converted to fake data using a detailed HRS simulation program. Finally, the fake data were analyzed with the same programs and selection criteria

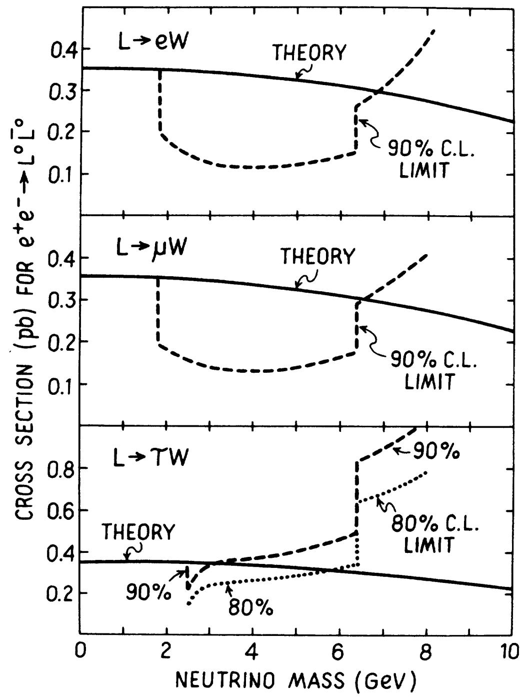

FIG. 5. Comparison of experimental cross-section limits and theoretical expectations for the production of massive neutrinos in $e^+e^-\to L^0\bar{L}^0$ at 29 GeV, as a function of neutrino mass in the limit of complete mixing $|U|^2=1$.

as were the real data.

We obtain limits on neutrinos as a function of both mass M and mixing $|U|^2$ by inserting the calculated detection efficiencies into Eq. (3). For prompt decays ($|U|^2=1$), event reconstruction efficiencies are shown in Fig. 4. They reach a maximum of about 0.23 at $M=4$ GeV for $L\to eW$ and $L\to\mu W$ and a maximum of about 0.14 at $M=5$ GeV for $L\to\tau W$. The $L\to\tau W$ efficiency is lower since many of the decay modes involve multiple light neutrinos and yield $e^\pm X^\mp$ pair masses that fall in-

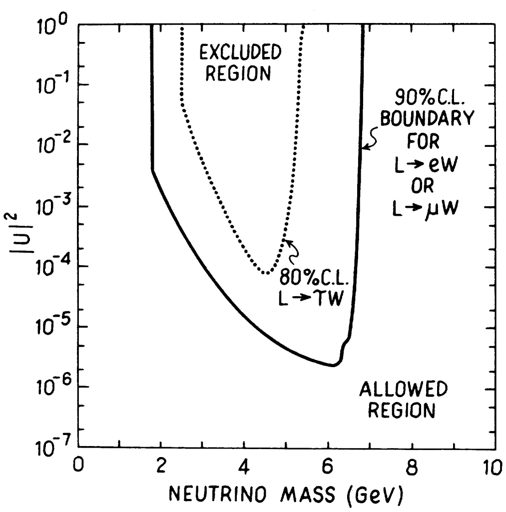

FIG. 6. Experimental limits on the production of massive neutrinos as a function of mass and mixing parameter $|U|^2$. The region surrounded by the curves is allowed, that outside the boundary is excluded.

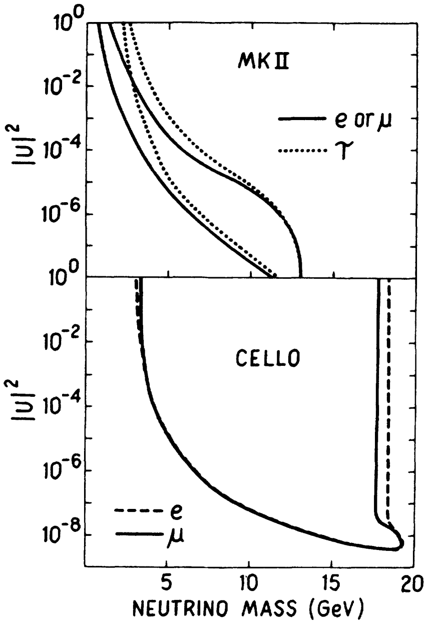

FIG. 7. Experimental limits on massive neutrinos obtained in other experiments: Mark II at PEP (Ref. 13) and CELLO at PETRA (Ref. 14). The Mark II contours represent 90%-C.L. limits, whereas those for CELLO at 95%-C.L. limits.

side the mass contour described above. As $|U|^2$ decreases, the proper lifetime of the neutrino increases and is given by the values shown in Fig. 1 divided by $|U|^2$. The detection efficiency decreases with increasing lifetime since the efficiency of the charged-particle tracking algorithm decreases for long decay paths. The efficiency falls roughly linearly with mean decay path length λ and, for neutrino masses around 4 GeV, it is reduced by approximately a factor of 2 when $\lambda = 0.20$ m. To obtain limits on neutrino production at a particular mass, $|U|^2$ was varied until the experimental cross-section limit, which depends on $|U|^2$ by way of the detection efficiency, was equal to the theoretically expected value.

The results of this search are summarized in Figs. 5 and 6. Figure 5 compares experimental cross-section limits for prompt decays ($|U|^2 = 1$) with theoretical expectations while Fig. 6 shows the regions of neutrino mass M and mixing parameter $|U|^2$ excluded by this study. The 90%-C.L. contours for $L \to eW$ and $L \to \mu W$ are almost identical and have been plotted as one curve in Fig. 6. The 90%-C.L. cross-section limits for $L \to \tau W$ are below the theoretical value over such a narrow mass range that the corresponding contour in Fig. 6 would not be very meaningful. We have, therefore, relaxed the confidence level to 80% for the $L \to \tau W$ limits and the corresponding results are shown in Fig. 6.

In conclusion, we have searched for massive neutrinos with standard-model couplings to the $W^{\pm}$ and Z^0 bosons and which mix with the known light neutrinos. We obtain significant limits on the existence of such neutrinos in the mass range from 1.8 to 6.7 GeV with mixing parameters $|U|^2$ as low as 3×10^{-6}. There have been numerous searches for additional, massive neutrinos based on semileptonic weak decays of various mesons. A review of such searches is given elsewhere.[11] These searches have relied directly on the mixing of neutrinos for their production and have yielded limits on neutrinos with masses below 2 GeV. The significance of the search presented here is that it is sensitive to pair production of new, massive neutrinos so that the production is not suppressed by mixing factors. The SLAC and DESY electron-positron colliders PEP and PETRA have been the first machines to open up the mass range 1–20 GeV to neutrino searches based on pair production. Limits on such neutrino production have also been obtained in other experiments at these machines by searching for identifiable, secondary vertices from unstable but long-lived neutrinos.[12,13] Evidence for massive neutrinos decaying to either electrons or muons ($L \to eW$, $L \to \mu W$) has also been sought by identifying electron-positron annihilation events with electron or muon pairs in the final state where one of the leptons is isolated in phase space.[14] The results from these other searches are summarized in Fig. 7. We note that the limits from this experiment presented in Fig. 6 and those from other experiments shown in Fig. 7 have been obtained using very different techniques. There is, however, substantial overlap in the regions of mass and mixing excluded by these experiments.

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