SEARCH FOR HEAVY NEUTRAL LEPTONS IN e^+e^- ANNIHILATIONS AT 29 GeV

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Received 24 September 1984

A search was made in 29 GeV e^+e^- annihilations for heavy, neutral leptons decaying to $e^\pm X^\mp(\nu)$, where X is a muon or charged meson. Six events with isolated $e^\pm X^\mp$ pairs were found for an integrated luminosity of 106 pb^{-1}. The expected background is 5.5 ± 2.2 events. Limits on $\sigma \cdot B$ depend on mass and range from 8 to 20×10^{-5} nb.

1. Introduction. Electron–positron annihilation has been a very effective process for the discovery and study of new charged particles. The primary reasons for this are the universal nature of the electromagnetic interaction and the great simplicity of the one-photon intermediate state. It is now well established that the electron–positron system interacts also via a second fundamental boson, Z^0 [1]. Unlike the photon, the Z^0 also couples universally to *neutral* fermions and therefore adds, in principle, a new means for producing and discovering new neutral particles such as massive neutrinos [‡1]. PEP and PETRA are the first electron–positron colliders with sufficient energy to yield a measurable event rate for Z^0 mediated annihilations [3,4].

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[‡1] For a discussion of massive neutrinos and an extensive list of relevant references see ref. [2].

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(North-Holland Physics Publishing Division)

For example, a reaction such as $e^+e^- \to \nu\bar{\nu}$ has a cross section of 3×10^{-4} nb which gives, for typical luminosities, about 30 events per year per collision region.

This paper describes a search for a possible heavy neutral lepton L^0 in the production and decay process:

$$e^+e^- \to L^0\bar{L}^0 \hookrightarrow e^\pm X^\mp(\nu)\,, \qquad (1)$$

where X is a charged, minimum-ionizing particle such as a muon or pion and where any light final-state neutrinos, ν, are undetected. The experimental signature consists of an isolated $e^\pm X^\mp$ pair, indicative of the weak decay of a neutral particle, recoiling against the unspecified decay fragments of the other heavy neutral lepton in the reaction. As shown below, the background rate for this configuration from known physical sources is very low and hence a sensitive search for such new particles is feasible. The possibility of the existence of massive lepton doublets beyond the τ family or of massive right-handed neutrinos makes such a search an important component of e^+e^- annihilation physics.

The search was carried out with the High Resolution Spectrometer (HRS) at PEP at a CM energy of 29 GeV. The total integrated luminosity for the data presented here is 106 ± 5 inverse picobarns. The detector has been described in detail elsewhere [5] [‡2]. Features of the HRS important to this search include charged-particle tracking over 90 percent of the full solid angle in a 1.6 T solenoidal magnetic field, and measurements of electromagnetic shower energy with a lead-scintillator calorimeter which covers the angular intervals $|\cos\theta| < 0.60$ and $0.70 < |\cos\theta| < 0.96$ where θ is the angle with respect to the beam direction. The central region of the calorimeter is segmented azimuthally by 40 independent modules whereas each endcap is divided into 20 sections. Showers are located by proportional wires (PWC's) with a position resolution of ±2 cm.

2. Selection criteria. Events were selected which contained at least one isolated charged-particle pair $e^\pm X^\mp$. Each event was required to satisfy the following criteria:

(a) The observed number of charged particles $\geqslant 4$ and the sum of the magnitudes of the charged particle momenta $\Sigma|p| > 7$ GeV/c.

(b) $|\cos\theta| < 0.866$ and momentum $p > 1.0$ GeV/c for each particle in the pair.

(c) Sum of magnitudes of momenta $4.5 < (P_e + P_X) < 17.0$ GeV/c.

(d) Opening angle of pair <60°.

(e) No other charged particle or photon with $E_\gamma > 0.1$ GeV in the hemisphere centered on the momentum vector of the pair.

(f) Identification of the electron by demanding the presence of a shower within 10 cm of the track and with a deposited energy E such that $0.7 < E/p < 1.3$. The detection efficiency for electrons is $\geqslant 90\%$.

(g) Identification of the minimum-ionizing particle by requiring that the associated shower energy be less than 0.5 GeV. The typical energy deposited by cosmic ray muons was measured to be 0.2 GeV and 90 percent of such muons deposited less than 0.5 GeV. Approximately 70 percent of incident pions deposited less than 0.5 GeV.

To allow clean particle identification, the tracks of each isolated $e^\pm X^\mp$ pair were required to strike separate shower counter modules. The calorimeter PWC signals from each track in the pair were required to be consistent with a single particle striking the appropriate module.

A total of 7 events were found satisfying all of the criteria. One of the events was rejected from consideration since it was completely consistent with the higher-order QED reaction $e^+e^- \to e^+e^-\mu^+\mu^-$. The characteristics of the remaining 6 events are listed in table 1.

3. Backgrounds. A number of known physical and instrumental effects will also satisfy the selection criteria described above yielding a background for this search. They include the following:

(a) A charmed particle jet consisting of a single neutral charmed D meson decaying to $K^\pm e^\mp \nu$ or $K^0_L \pi^\pm e^\mp \nu$.

(b) A charmed particle jet consisting of $D^\pm \pi^\mp$ where the charged D decays to $K^0_L e^\pm \nu$.

(c) A jet consisting of two charged hadrons $X^\pm X^\mp$ where one hadron interacts in the shower counter to mimic an electron.

(d) A jet consisting of two charged hadrons and one neutral pion, where the latter overlaps one of the

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[‡2] The HRS has no detectors for distinguishing muons from other particles.

Table 1
Events with isolated $e^\pm X^\mp$ pairs [a)].

Run	Event	Pair	$e^\pm X^\mp$ pair			Opposite jet			
			p_e (GeV/c)	p_X (GeV/c)	mass (GeV/c^2)	N_{ch}	ΣP_{ch}	ΣE_γ	mass (GeV/c^2)
4431	17910	e^+X^-	5.43	9.09	1.68	$\geqslant 4$	$\geqslant 3.1$	9.4	$\geqslant 5.2$
4859	19074	e^-X^+	2.07	2.75	0.33	2	5.2	3.3	1.5
5281	2869	e^-X^+	7.02	4.31	1.30	$\geqslant 4$	$\geqslant 10.5$	$\geqslant 1.5$	$\geqslant 1.9$
5282	8871	e^+X^-	5.84	2.83	1.04	6	11.4	3.3	5.2
5308	14463	e^-X^+	3.49	2.34	0.81	2	3.0	10.2	$\geqslant 6.3$
5363	11940	e^+X^-	2.55	2.70	1.58	6	7.5	6.7	5.8

[a)] $e^\pm X^\mp$ masses are calculated using $m_e = m_X = 0$. $N_{ch} \equiv$ number of charged particles; $\Sigma P_{ch} \equiv$ sum of magnitudes of charged particle momenta; ΣE_γ = sum of calorimeter energies not associated with charged tracks.

charged particles giving a false electron signal.

(e) $e^\pm X^\mp$ pairs accompanied by photons or neutral pions which enter the interval $0.60 < |\cos\theta| < 0.70$ not covered by the calorimeter. $D^* \to D^0\gamma$ and $D^* \to D^0\pi^0$ decays contribute to this background.

The number of events expected from each of these sources was estimated directly from the data. The use of Monte Carlo techniques was limited to calculating geometrical detection efficiencies.

The charmed particle backgrounds (a) and (b) were estimated by first determining the fraction of charmed particle jets consisting of a single D or a $D\pi$ pair. This was accomplished by examining 150 events containing D^* rather than D^0 or $D^\pm$ candidates because D^*'s are identified with very little background and the kinematical properties of D^* and direct D jets are likely to be very similar [6]. Four events were found to contain an isolated D^* and another four an isolated $D^*\pi^\pm$ pair. The number of background events in (a) is then given by:

$$\sigma_{D^0} \cdot [B(D^0 \to K^\pm e^\mp \nu) + B(D^0 \to K^0_L \pi^\pm e^\mp \nu)]$$
$$\times \tfrac{4}{150} \epsilon \int L \, dt\,, \qquad (2)$$

where σ_{D^0} is the inclusive *direct* D^0 production cross section, B stands for decay branching fraction, ϵ is the detection efficiency for the resulting $e^\pm X^\mp$ pair and $\int L \, dt = 106\ \mathrm{pb}^{-1}$ is the integrated luminosity. The cross section σ_{D^0} (or equivalently the ratio σ_D/σ_{D^*}) is not well known. HRS data are consistent with no direct D^0 production but can accomodate, within errors, a ratio $\sigma_D/\sigma_{D^*} = 1/3$ expected from simple spin arguments [7]. With a ratio of 1/3 (or $\sigma_{D^0} = 0.041$ nb), a sum of branching fractions [‡3] equal to 0.04, and with a calculated value $\epsilon = 0.23$, one obtains 1.1 ± 0.6 events for (a). Similarly, with a value [‡4] of 0.05 for $B(D^\pm \to K^0_L e^\pm \nu)$, 1.4 ± 0.7 events are expected from (b).

Background (c) was estimated by measuring the probability that a charged pion interacts in the shower counters in such a way as to satisfy the electron identification requirements. A sample of pions was selected from three-prong tau-lepton decays. The probability for such pions to mimic electrons was found to be $8.3 \pm 2\%$ in the momentum range 1–2 GeV/c $(3.7 \pm 1.0)\%$ for 2–5 GeV/c and $(1.8 \pm 1.2)\%$ above 5 GeV/c. Data corresponding to an integrated luminosity of 86 pb^{-1} yielded 18 isolated X^+X^- pairs satisfying the criteria given above. Assuming that these are pions, one then obtains 1.4 ± 0.3 false $e^\pm X^\mp$ pairs for 106 pb^{-1} where the average probability for a pion to fake an electron is 3.2% for the observed momentum distribution.

Background (d) was determined by selecting events with charged particle pairs accompanied by a single, additional, resolved shower counter signal in the hemisphere centered on the pair momentum vector. The energy E corresponding to this additional shower was

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[‡3] Ref. [8] gives $B(D^0 \to e^+ + \text{anything}) = 0.055 \pm 0.037$. We assume equal decay rates to K and K^*.

[‡4] We use $B(D^+ \to e^+ + \text{anything}) = 0.19$ from ref. [9] and assume equal decay rates to K and K^*.

required to give an E/p ratio in the range from 0.7 to 1.3 when added to one or the other track. The remaining track was required to be consistent with a minimum-ionizing particle. Data corresponding to 86 pb^{-1} yielded six such events. The shower positions in these events were at distances from 20 to 250 cm from the appropriate tracks. From these data it is estimated that 106 pb^{-1} would yield 0.4 ± 0.2 events in which the additional shower randomly satisfies the requirement of being within 10 cm of the appropriate track and where the E/p ratio is in the range 0.7 to 1.3.

Finally, background (e) was estimated by determining the number of $e^{\pm}X^{\mp}$ pairs that were accompanied by an additional, single shower counter signal with $E_{\gamma} > 0.1$ GeV in the hemisphere centered on the pair momentum vector. Eleven such events were found for 106 pb^{-1} with an additional shower energy ranging from 0.2 to 3.6 GeV. The probability for photons with a $(1 + \cos^2\theta)$ distribution to enter the gap $0.6 < |\cos\theta| < 0.7$ is 0.11. The number of $e^{\pm}X^{\mp}$ (γ or π^0) events in which the additional neutral particle is missed is therefore estimated to be 1.2 ± 0.4.

In addition to (a)–(e), the reaction $e^+e^- \to e^+e^-$ + hadrons represents another possible source of background which is expected to be small but which is difficult to estimate. None of the six observed events contain an identifiable e^+e^- pair. Five of the events have a relatively small (<3 GeV/c) imbalance in the longitudinal momentum making it unlikely that a small-angle electron escaped detection. The sixth event shows a longitudinal momentum imbalance of about 5.5 GeV/c but the missing momentum vector points well into the active volume of the detector in the direction of the e^+X^- pair.

Table 2
Backgrounds for $e^{\pm}X^{\mp}$.

	Background source	Expected number of events
(a)	$D^0 \to K^{\pm}e^{\mp}\nu$ $\to K^0_L\pi^{\pm}e^{\mp}\nu$	1.1 ± 0.6
(b)	$D^{*\pm}\pi^{\mp} \to K^0_L e^{\pm}\nu\pi^{\mp}$	1.4 ± 0.7
(c)	(interacting $X^{\pm}$) $X^{\mp}$	1.4 ± 0.3
(d)	$(X^{\pm}\pi^0)\, X^{\mp}$	0.4 ± 0.2
(e)	$e^{\pm}X^{\mp}$ (missed γ's)	1.2 ± 0.4
	Total	5.5 ± 2.2

The backgrounds described above are summarized in table 2. These known sources are expected to yield 5.5 ± 2.2 events with an isolated $e^{\pm}X^{\mp}$ pair.

4. Results and conclusion. The search for heavy, neutral leptons decaying to $e^{\pm}X^{\mp}(\nu)$ yielded six events, a number which is consistent with the 5.5 ± 2.2 events expected from known background sources. The sensitivity of this measurement is indicated qualitatively by noting that a short-lived, sequential neutrino with a mass of a few GeV/c^2 and a $\mu^{\pm}e^{\mp}\nu$ branching fraction of 20% would have yielded 3.6 ± 1.9 events with isolated $e^{\pm}X^{\mp}$ pairs satisfying the selection criteria. None of the observed $e^{\pm}X^{\mp}$ pairs originated from resolvable secondary decay vertices. Such vertices would be observable for lepton lifetimes in the range from about 10^{-11} to 10^{-10} s. Results from a more general search for long-lived heavy neutrinos will be presented elsewhere.

The best upper limits on $(\sigma_L + \sigma_{\bar{L}}) \cdot B(e^{\pm}X^{\mp}\nu)$ for leptons with lifetimes $\lesssim 10^{-11}$ s are obtained by taking into account the observed masses of the $e^{\pm}X^{\mp}$ pairs and of the jets of visible particles recoiling against them. None of the six events have an $e^{\pm}X^{\mp}$ mass above 2 GeV/c^2 while at most two events have a recoil jet mass below this value. Table 3 summarizes 90% confidence level upper limits as a function of lepton mass. These limits vary from 8 to 20 × 10^{-5} nb. For $m_L \geqslant$ 3 GeV/c^2 the additional analysis requirement of $m_{eX} > 2$ GeV/c^2 is imposed and reflected in the detection efficiency. The limits in table 3 are given for the case

Table 3
Upper limits (90% CL) for $(\sigma_L + \sigma_{\bar{L}}) \cdot B(e^{\pm}X^{\mp}\nu)$.

Mass of L (GeV/c^2)	Events consistent with m_L and with m_{eX} cut	Detection [a] efficiency	Limit $\sigma \cdot B$ (10^{-5} nb)
1	0	0.28	8
2	2	0.28	18
3	0	0.11	20
4	0	0.20	11
5	0	0.20	11
6	0	0.17	13
7	0	0.13	17

[a] Includes the requirement $m_{eX} > 2$ GeV/c^2 for $m_L \geqslant 3$ GeV/c^2.

where particle $X^{\mp}$ of the $e^{\pm}X^{\mp}$ pair is a muon. If it is a meson, the limits are 20% higher.

The expected value of σB for a heavy neutral lepton depends on the nature of such a lepton. If $L^0 \to e^- W^+$ or $L^0 \to \mu^- W^+$, where W^+ is a virtual intermediate boson, then branching ratios of about 20% can be expected for $L^0 \to e^{\pm}\mu^{\mp}\nu$ when $m_L \lesssim 3\ \mathrm{GeV}/c^2$. This yields $\sigma \cdot B = 12 \times 10^{-5}$ nb if L^0 couples to the Z^0 with the same strength as a light neutrino. For higher masses this branching ratio is expected to decrease to about 11% ($\sigma \cdot B = 7 \times 10^{-5}$ nb). Perhaps a more likely decay for more massive leptons is $L^0 \to \tau^- W^+$ yielding $e^-\mu^+$, $\mu^- e^+$ and $\pi^- e^+$ pairs. In this case $\sigma \cdot B$ for $L^0 \to e^{\pm}X^{\mp}(\nu)$ is estimated to be 6×10^{-5} nb. The limits in table 3 are close to these expected values of $\sigma \cdot B$ but are not yet conclusive. An improvement of the experimental sensitivity to the definitive level of 6×10^{-5} nb requires several additional years of data at PEP (or PETRA) or a pooling of results from several experiments.

Heavy neutral leptons have also been sought elsewhere in $\tau \to \nu_\tau e N$ and $\tau \to \nu_\tau \mu N$ where N decays to $e\pi$ or $\mu\pi$ [10], in muon induced reactions ($M^0 \to \mu^+\mu^-\nu$) [11], in $e^+e^- \to E^0\bar{\nu}_e$ where E^0 is a heavy electron neutrino [12] and in a beam dump experiment ($\nu_\tau \to e^+e^-\nu_e$) [13]. The results from these searches are not directly comparable to those presented here because of differences in reactions and decay final states.

This work was supported by the US Department of Energy and in part by the Sloan and Guggenheim Foundations. We are grateful to the staff of the Stanford Linear Accelerator Center for their support of this research. In particular, we acknowledge helpful discussions with M. Perl and Y.S. Tsai.

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