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Search for Heavy-Neutrino Production in e^+e^- Annihilation at 29 GeV

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We report a search for long-lived heavy neutrinos produced by the neutral weak current in e^+e^- annihilation at 29 GeV at the SLAC storage ring PEP. Data from the Mark II detector are examined for evidence of events with one or more separated vertices in the radial range of 2 mm to 10 cm. No events were found that were consistent with the search hypothesis, ruling out heavy neutrinos with mean decay lengths of 1 to 20 cm in the mass range 1 to 13 GeV/c^2.

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There is a natural interest in looking for fermions belonging to a fourth family as the simple extrapolation of the structure already observed. Supposing that neutrinos have masses which progress like the e, μ, and τ masses and considering the limits on masses of ν_e, ν_μ, and ν_τ, one easily imagines a fourth neutrino at several GeV/c^2. Aside from this naive consideration, searching for such heavy neutral leptons is especially interesting because they appear in conjunction with the "see-saw" mechanism in left-right-symmetric models[1] and models of horizontal gauge symmetry,[2] and also in the O(18) family unification model which predicts five additional neutral leptons below 40 GeV/c^2.[3] In each of these scenarios the possibility exists that the particles would be produced in an e^+e^- collider and their flight paths before decay would be observable.

We are reporting a search for long-lived heavy-neutrino pairs produced by the neutral weak current in e^+e^- annihilation at 29 GeV at the SLAC storage ring PEP.[4] Although this search applies also to other long-lived heavy neutral particles, we have parametrized the results in terms of an hypothesized fourth-generation massive Dirac neutrino ν_4. This neutrino is supposed to occur in a fourth leptonic family together with a charged lepton l_4^- which is so heavy that it has not yet been observed. If the fourth family were to mix principally with one other family, say τ, the weak isodoublets could be written[5]:

$$\begin{pmatrix} \nu_\tau\cos\epsilon + \nu_4\sin\epsilon \\ \tau^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_4\cos\epsilon - \nu_\tau\sin\epsilon \\ l_r^- \end{pmatrix}_L.$$

For appropriate values of the Cabibbo-type mixing angle ϵ, the path length before decay of the ν_4 (Fig. 1) would be experimentally observable. Unitarity of the mixing matrix and measurements of e-μ and τ-μ weak universality[6,7] place constraints on the experimentally allowed mixings. For example, if ν_4 mixed only with ν_τ then the τ lifetime measurement requires $\sin^2\epsilon < 0.20$ at the 90% confidence level.

In this model, the lifetime of the heavy neutrino is calculable given the mixing angle ϵ. It can be expressed in terms of the muon lifetime as

$$\tau(\nu_4 \to l^- X^+) = \left(\frac{m_\mu}{m_4}\right)^5 \frac{\tau(\mu \to e\nu\bar{\nu})B(\nu_4 \to l^- e^+ \nu)}{f(m_4, l)\sin^2\epsilon},$$

where m_4 is the mass of ν_4, l represents the lepton (e, μ, or τ) to which ν_4 primarily couples, and f is a phase-space correction which differs appreciably from unity only when $l = \tau$. We have calculated the partial widths for the various ν_4 decay modes in analogy with the case of τ decay,[8] obtaining the branching fraction $B(\nu_4 \to l^- e^+ \nu)$ as a function of m_4 and l. We found that B varies between 0.20 and 0.12 over the mass range relevant to our search. For the case $l = \tau$, the result of the phase-space integration can be approximated as

$$1/f(m_4, \tau) \cong 1 + 15/\Delta m^4 - 15/\Delta m^3 + 20/\Delta m^2$$

where $\Delta m = m_4 - m_\tau$.

The cross section for producing a $\nu_4\bar{\nu}_4$ pair via the

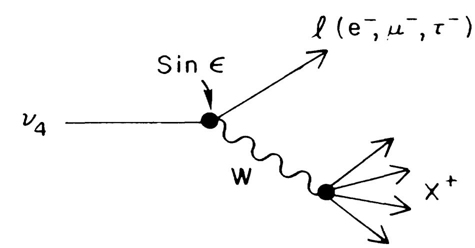

FIG. 1. ν_4 decay.

weak neutral current in e^+e^- annihilation is

$$\frac{d\sigma}{d\cos\theta}=\frac{1}{64\pi}\frac{G_F^2 s}{(1-s/M_Z^2)^2+\Gamma_Z^2/M_Z^2}[(1-4\sin^2\theta_W+8\sin^4\theta_W)\beta(1+\beta^2\cos^2\theta)+2(1-4\sin^2\theta_W)\beta^2\cos\theta],$$

where θ measures the angle of production with respect to the e^+e^- beam axis, β is the speed of the particles produced in the center-of-mass frame, and $\sqrt{s}$ is the center-of-mass energy. At the PEP energy of 29 GeV, this cross section is only 0.34 pb,[9] but the accumulated Mark II data of 208 pb^{-1} would yield 71 produced events and thus allow a reasonable search.

The search was conducted with the Mark II detector at PEP. The detector has been described in detail elsewhere.[10] We recall here the details relevant to this analysis. In the following, z is the coordinate along the beam axis, the xy plane is perpendicular to it, and $r_{xy}^2=x^2+y^2$. The origin is defined by the center of the main drift chamber. Charged particles are tracked by the combination of a high-precision drift chamber, known as the vertex chamber, and a main drift chamber which surrounds it. The vertex chamber has one band of axial sense wires arranged into four layers near $r_{xy}=11.2$ cm and another band of three layers near $r_{xy}=31.2$ cm. The main drift chamber consists of sixteen layers of axial and stereo sense wires in the range 41.4 cm $< r_{xy} <$ 144.8 cm. Together these chambers track charged particles efficiently for $|\cos\theta|<0.80$, where θ is the polar angle between the track and the beam axis. They are immersed in a 2.3-kG axial magnetic field. When projected onto the xy plane, the resolution σ_b in the extrapolation of tracks is approximately $\sigma_b=(95\ \mu\text{m})\ (1+1/p_{xy}^2)^{1/2}$ near the collision point, where p_{xy} is the xy projection of track momentum in GeV/c. The momentum-dependent term in σ_b is mostly due to multiple Coulomb scattering. Photons are detected by a liquid-argon calorimeter yielding an energy resolution $14\%/\sqrt{E}$ (E in gigaelectronvolts) for $|\cos\theta|<0.70$.

The basic strategy was to look for events with two back-to-back vertices that are separated from the interaction point and with no tracks coming from the interaction point. There are several ways hadronic events might simulate this signature. Charm and bottom decays can give rise to back-to-back displaced vertices, and tracking inefficiencies and statistical fluctuations could cause there to be no additional reconstructed primary tracks. However, by our requiring each decay to be further than 2 mm from the beam, this background becomes negligible. Another mechanism is due to the presence of fake secondary vertices. These can arise from strange particle-decay tracks, tracking errors, and untracked motion of the interaction point. For example, the primary could move to one side of the assumed beam position, and a fake vertex might appear on the other. To minimize these possibilities, we required certain tracks in an event to satisfy tracking quality cuts, eliminated K_S and Λ decay tracks from consideration, and removed runs where the beam position was unstable.

Candidate events were required to have charged energy $E_{\text{ch}}>3.6$ GeV and total energy $E_{\text{tot}}>7$ GeV. They also had to have four or more charged tracks, since each ν_4 must decay into at least two charged particles. There must have been no primary vertex within $r_{xy}<1$ mm, where the vertex was defined as any three tracks each passing within $2\sigma_b$ of the same point in the xy plane. (The beam spot size is approximately 1 mm wide and 0.3 mm high.) Also, two good tracks had to miss the interaction point by 3 standard deviations.[11] We considered a good track one which had at least two hits in the innermost band of four layers in the vertex chamber, did not overlap another track near these hits, had ≥ 12 hits total with χ^2 per degree of freedom <10, and satisfied 200 MeV/$c<p_{xy}<15$ GeV/c. This requirement of hits in the vertex chamber is needed because incorrect assignment of hits in the four innermost layers leads to a large error when extrapolating a track to the interaction region. Also, if the track-fitting routine was not able to assign hits in these layers to a given track, it may be because there was a kink in the track due to scattering or decay in flight. For real events with charged multiplicity similar to the hypothesized signal, about 70% of tracks (which are otherwise satisfactory) satisfy the vertex chamber hits requirement.

We defined the signal by identifying one or both decay vertices occurring on opposite sides of the interaction point. We used only tracking information in the xy plane, since the resolution is much poorer in the z direction. Because the major backgrounds are different, we treated separately events with four tracks and events with more than four.

For four-prong events, we required two two-prong forward decays each with charge zero, on opposite sides of the interaction point, inconsistent with the interaction point at the level[12] $\chi^2>9$ and separated from it by at least 2 mm. At least one vertex had to consist of two good tracks (as defined above) and satisfy $r_{xy}<10$ cm. The prongs from the other vertex did not have to be good tracks. The back-to-back condition stated that the angle between the two decays and centered at the beam spot had to be 180° to within 14° or 3 standard deviations. The forward decay stipulation disallowed any track which decayed more than 150° from the flight path of the decaying particle (90° if the track passed within 2 standard deviations[11] of the beam spot).

If there were more than four tracks in an event, we required one vertex with at least three prongs to be in the range 2 mm $<r_{xy}<$ 10 cm and inconsistent with the interaction point with significance[12] $\chi^2 > 9$. Specifically we searched for the point in 2 mm $< r_{xy} <$ 10 cm consistent with the largest number of forward-decaying good tracks. A track was considered consistent with a point if it passed within $3\sigma_b$ and 500 μm of that point. We attempted similarly to group any remaining good tracks into a vertex on the opposite side with 2 mm $< r_{xy} <$ 10 cm. If the first vertex was less than 3 mm from the beam-spot center, we required a second decay vertex to exist. (This removed hadronic events where the primary interaction was in the tail of the beam-spot distribution.) In general some good tracks were not assignable to either vertex, tending to contradict the hypothesis of back-to-back decays. We rejected the event if any such tracks passed within 2 standard deviations[11] of the e^+e^- interaction point. (In the hadronic background many tracks are consistent with the primary.) If the main decay vertex had only the minimum three tracks and there was no back-to-back vertex found, we allowed no unassigned good tracks; otherwise, we allowed up to two. An event was rejected if the main decay vertex was consistent with an interaction in the beam pipe, 7.41 cm $< r_{xy} <$ 8.01 cm.

After applying these cuts, only three events remained. (A Monte Carlo simulation predicted that we would see two events from hadronic background at this point in the analysis.) On further examination of these events, we found that they were all incompatible with the hypothesis of ν_4-pair production. In one event the position of the beam spot had moved 3 mm from its assumed position. This was determined by an examination of the primary vertex of the events immediately preceding and following the candidate event. A second event had only three charged particles present. The remaining tracks were from two independent photon conversions in the chamber. The final event was kinematically incompatible with the ν_4-pair hypothesis because it had a backward-going 8-GeV/c track. We interpret the result as zero signal events.

The acceptance of this search was primarily limited by two effects. The requirement that both decays occur beyond 2 mm and that one occur inside 10 cm defined the shape of the efficiency curve as a function of mean decay length. When the decays were in the sensitive region, the efficiency was restricted by the requirement of two good hits in the innermost four layers of wires for each track used to define a vertex. A Monte Carlo event generator was written which simulated ν_4 decays in all modes as well as details of the detector. The final acceptance curve was obtained by our interpolating between Monte Carlo results at discrete values of m_4 and mean decay length, using an analytical estimate of the shape of the curve as a guide. In this way we refined our estimate of the curve's normalization and also included other effects which caused gradual variation of acceptance with the parameters. An adjustment was made in the Monte Carlo program because the efficiency of the tracking quality cuts for real hadronic data was found to be only 90% of that predicted by the Monte Carlo. Without this adjustment, acceptance would be overestimated by a factor 1.2. About 9% of the data was unusable because of the beam stability requirement. We also considered the effect of uncertainties in tracking precision, in calculations of branching fractions for ν_4 decays, in luminosity and in possible extra noise tracks in real data events. Each of these effects causes a systematic uncertainty in the acceptance; added in quadrature they would shift our maximum acceptance from 28% up to 31% or down to 25%. In order to quote a conservative limit, we adjusted all our calculated acceptances downward by this quadratic sum.

Figures 2 and 3 show the excluded regions for m_4 versus decay length and m_4 vs $\sin^2\epsilon$ at the 90% confidence level. Figure 2 shows that decay lengths between 1 and 20 cm are excluded for $1 < m_4 < 13$ GeV/c^2. The edge of the region at $m_4 \cong 13$ GeV/c^2 depends on production threshold factors. In Fig. 3 these results are translated to limits on $\sin^2\epsilon$ between unity and 10^{-8} depending on m_4.

For a recent survey of other experiments covering vari-

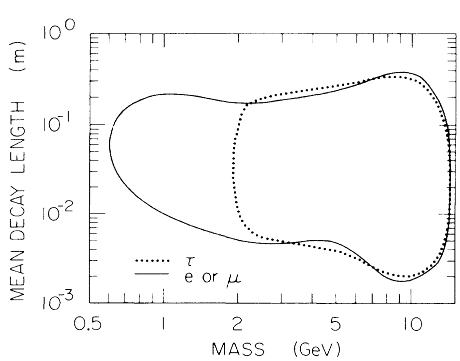

FIG. 2. The interiors of the curves are excluded at the 90% confidence level if ν_4 couples to e, μ, or τ.

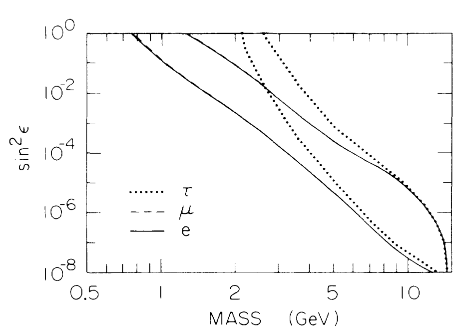

FIG. 3. Excluded region for ν_4 at the 90% confidence level as a function of $\sin^2\epsilon$ and m_4.

ous regions of the m_4 vs $\sin^2\epsilon$ plane, see the work of Gilman.[13] Also, Badier *et al.* (NA3 collaboration) have recently looked for ν_4 up to 2 GeV including somewhat smaller mixing angles than those we were able to consider.[14] A search similar to ours has been carried out with the CELLO detector at the DESY storage ring PETRA, with similar results.[15]

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[9]This value allows for a -5% radiative correction. We have used the values $G_F = 1.166\times10^{-5}$ GeV^{-2} for the Fermi constant, $M_Z = 93$ GeV and $\Gamma_Z = 2.7$ GeV for the mass and width of the Z^0, and $\sin^2\theta_W = 0.219$ for the weak mixing angle.

[10]R. H. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981); J. A. Jaros, in Proceedings of the International Conference on Instrumentation for Colliding Beam Physics, Stanford, California, 1982, edited by W. Ash, Stanford Linear Accelerator Center Report No. 250 (unpublished), p. 29.

[11]Here the standard deviation in the impact parameter of a track with respect to the interaction point, which we call σ_t, combines the extrapolated track-measurement error and the error ellipse defining the beam spot: $\sigma_t^2 = \sigma_\delta^2 + \sigma_x^2 \sin^2\phi + \sigma_y^2 \cos^2\phi$, where σ_x and σ_y measure the beam spot size and ϕ is the azimuthal angle of the track with respect to the x axis.

[12]This quantity reflects the uncertainty in the distance between two error ellipses, one fixed by the uncertainties for tracks used in the construction of a decay vertex position and the other given by the beam spot size. The significance of separation of two points with error ellipses is given in terms of the separation $(\Delta x, \Delta y)$ and the sum of error matrix terms σ_{xx}, σ_{xy}, and σ_{yy} by

$$\chi^2 = \frac{\sigma_{yy}\Delta x^2 + \sigma_{xx}\Delta y^2 - 2\sigma_{xy}\Delta x \Delta y}{\sigma_{xx}\sigma_{yy} - \sigma_{xy}^2} .$$

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