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A SEARCH FOR DECAYS OF THE Z TO UNSTABLE NEUTRAL LEPTONS WITH MASS BETWEEN 2.5 AND 22 GeV*

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ABSTRACT

Using the sample of neutral vector bosons (Z's) produced at the SLAC Linear Collider and detected with the MARK II detector, we search for the decay of the Z to a pair of particles, one of which decays to two charged particles. The observed number of Z decays with this signature excludes, at a confidence level greater than 95%, the decay of the Z to a pair of fourth-generation, Dirac neutrinos with mass between 2.5 and 22 GeV, decay length less than about 1 cm, and coupling to any of the first three generations of charged leptons. This is the first time the existence of such a lepton coupling to the $\tau^{\pm}$ has been excluded by a direct search.

The Standard Model of particle physics does not predict the number of generations of fundamental fermions. The existence or absence of a fourth generation must be determined experimentally. A simple extension of the mass structure of the known fermions would indicate that the neutral lepton ν_4 would be the lightest member of the fourth generation and hence the most kinematically accessible with current experiments.

The decay products of the neutral member of the weak vector bosons, the Z, provide an excellent and unique hunting ground for new neutral leptons since the branching fraction of the Z to a pair of fourth-generation, Dirac neutrinos $\nu_4\bar{\nu}_4$ is expected to be large, approximately $(\beta/4)(3+\beta^2)\cdot 6.3\%$ where β is the velocity of the ν_4 in the Z rest frame. The MARK II data sample consists of 528 Z decays ($19.7\ \mathrm{nb}^{-1}$) produced through e^+e^- annihilation with the SLAC Linear Collider (SLC) at center-of-mass energies between 89.2 and 93.0 GeV. The expected number of produced $\nu_4\bar{\nu}_4$ events in this data sample is at least 40 for a ν_4 mass less than about 10 GeV, dropping to 35 events for a ν_4 mass of 22 GeV.

Three analyses pertaining to searches for new neutral leptons have already been conducted with the SLC data sample. The analyses differ in the range of ν_4 masses m_4 and lifetimes to which they are sensitive. If the charged partner L^- of the ν_4 is heavier than the ν_4 and if the neutrino mass eigenstate ν_4 is also the weak eigenstate ν_L, then the neutrino is stable. However, if the weak eigenstates of the neutrinos ν_ℓ ($\ell = e, \mu, \tau, L$) are mixtures of the mass eigenstates ν_i ($i = 1, 2, 3, 4$)

$$\nu_\ell = \sum_{i=1}^{4} U_{\ell i}\nu_i \quad ,$$

where $U_{\ell i}$ is a unitary mixing matrix, then the ν_4 can couple to the lighter charged leptons through the charged weak current $\nu_4 \to \ell^- W^+$ ($\ell^- = e^-, \mu^-, \tau^-$) with $(V - A)$ coupling at the W vertex. A simple analogy with the mixing structure of the quark sector would indicate that the ν_4 would couple most strongly to the third generation charged lepton, the $\tau^{\pm}$. Assuming the ν_4 mixes with only one other lepton generation, the lifetime of the ν_4 can be expressed in terms of the muon lifetime as

$$\tau(\nu_4) = \left[\frac{m_\mu}{m_4}\right]^5 \frac{\tau(\mu) Br(\nu_4 \to \ell^- e^+ \nu_e)}{|U_{\ell 4}|^2 f} \quad ,$$

where f is a phase-space suppression factor[1] for massive final state particles which differs appreciably from unity when one or more of the final state particles is a τ lepton or charm quark, and m_4 is relatively small.

The results of previous searches for a new neutral lepton coupling to $\tau^{\pm}$ are shown in Fig. 1 as excluded regions in a log-log plot of m_4 versus $|U_{\tau 4}|^2$. Note that in this plot contours of constant lifetime would be approximately straight lines with negative slope. The measurement at SLC of the partial width of the Z to invisible decay modes[2] eliminates a new neutral lepton[3] with mass less than about 20 GeV and mean decay length[4] greater than about 10 cm (region b enclosed by the inner solid line in Fig. 1). A search for events at SLC with an energetic, isolated track[5] excludes a new neutral lepton with mass between about 20 and 43 GeV and decay length less than about 1 cm (region c enclosed by the inner dotted line in Fig. 1). Finally, a search for events at SLC with a large fraction of tracks with high impact parameter to the e^+e^- interaction point[6] excludes a ν_4 with mass in the range of 10 to 43 GeV and mean decay length between about 1 cm and 1 m (region d enclosed by the inner dashed line in Fig. 1). A search conducted with the MARK II detector at PEP[7] already excludes a ν_4 with mass less than about 12 GeV and mean decay length between about 1 and 20 cm (region e enclosed by dash-dotted line in Fig. 1). All of these searches are sensitive to the existence of a new neutral lepton which couples to the charged lepton of any of the first three generations: $e^{\pm}$, $\mu^{\pm}$ or $\tau^{\pm}$.

The measurements from LEP extend these excluded regions to higher values of m_4. Regions f, g, h and i in Fig. 1 correspond to the areas excluded by LEP, but not by MARK II, for ALEPH analyses[8] similar to those described in the previous paragraph. Region i is excluded by ALEPH from the measurement of the total hadronic cross section at the Z peak.

As can be seen from Fig. 1, the existence of a new neutral lepton with mass in the range 11.8 to 20 GeV and mean decay length less than about 1 cm is not excluded by the analyses described above. Unstable neutral leptons have been excluded over limited mass ranges for coupling to $e^{\pm}$ or $\mu^{\pm}$ by the CELLO[9] and AMY[10] collaborations through searches for events with two or more leptons, but have never been eliminated for coupling to the $\tau^{\pm}$ by any direct search.[11] In this Letter we describe a search for a fourth-generation, Dirac neutrino with a mean decay length less than about 1 cm and a mass in the range 2.5 to 22 GeV for coupling to the electron, muon or tau lepton. We include the mass range from 2.5 to 11.8 GeV since a ν_4 has not been excluded in this range by a direct search.

The strategy is to search for events in which the Z decays to two particles, one of which decays to a final state containing exactly two charged particles (and any number of visible or invisible neutral particles). This strategy is motivated by the following three points.

(1) For $m_4 \lesssim 22$ GeV, the event can be divided into hemispheres by a simple thrust analysis to quite accurately separate the decay products of the ν_4 and $\bar{\nu}_4$.

(2) The expected branching fraction of an unstable ν_4 to two charged particles is large, generally greater than one-third for the mass range considered in this analysis.

(3) The theoretical branching fraction of the Z to a new Dirac neutrino is large so that, given the size of our data sample, the number of produced events with a ν_4 decaying to two charged particles is expected to be $\gtrsim 15$ for the mass range considered. Conversely, the probability that a hadronic decay of the Z produces a jet of only two charged particles is small.

Since the main selection criteria for this search is based on counting charged tracks, the tracking system of the MARK II detector[12] is particularly important for this analysis. The tracking is provided by the central drift chamber which consists of twelve concentric cylindrical layers of six-sense-wire cells of jet-chamber geometry between radii of 19.2 cm and 151.9 cm. There are six axial and six stereo layers. The chamber is immersed in a 4.75 kG solenoidal magnetic field and has an intrinsic position resolution of less than 200 μm per wire, resulting in a charged-particle momentum resolution of $\sigma(p)/p^2 = 0.0046\ (\mathrm{GeV}/c)^{-1}$. A two-track separation efficiency of about 80% is measured for tracks separated by 3.8 mm. The MARK II data acquisition system is triggered either by two or more charged tracks with an angle θ with respect to the beam axis satisfying $|\cos\theta| < 0.76$, or by an electromagnetic shower with a localized energy deposition greater than 3.3 GeV in the barrel or greater than 2.2 GeV in the endcap electromagnetic calorimeters.

For this analysis, a reconstructed track in the drift chamber is used if the distance of closest approach to the interaction point is less than 4 cm in the plane perpendicular to the beam axis and less than 6 cm along the beam axis and if the measured momentum perpendicular to the beam axis is greater than 100 MeV. A shower of energy in one of the electromagnetic calorimeters is defined to be a neutral particle if the energy is greater than 500 MeV and the distance between the shower and the closest charged track is at least 5 cm.

To develop the exact selection criteria, we simulate the $\nu_4\bar{\nu}_4$ signal using Monte Carlo techniques. An important feature of our simulation is that the polarization and spin correlations of the ν_4 and $\bar{\nu}_4$ are calculated and incorporated in the decays.[13] For $\nu_4\bar{\nu}_4$ production at the Z, the longitudinal polarization of the ν_4 averaged over 4π of solid angle varies from -1.00 for $m_4 = 2.5$ GeV to -0.93 for $m_4 = 22$ GeV. The polarization affects the angular distribution of the decay products in the rest frame of the ν_4 and hence the measured energy of the charged particles in the laboratory frame.

The allowed decay modes, branching fractions and decay kinematics for ν_4 decay are determined by m_4 and by the difference in mass of the ν_4 and the charged lepton to which it couples. The branching fractions are calculated and the decay kinematics simulated by the same procedure that was used for a search for new lepton pairs with arbitrary neutrino mass[14] by the MARK II Collaboration at PEP. The differential decay rates for purely leptonic final states and for cases in which the virtual $W^{\pm}$ decays to single-hadron final states such as $\pi^{\pm}$, $\rho^{\pm}$, $a_1^{\pm}$, $K^{\pm}$ or $K^{*\pm}$ follow directly from weak-interaction theory. The Lund fragmentation model[15] is used to produce the multihadron final states from $W^+ \to u\bar{d}$ or $c\bar{s}$. The normalization of each hadronic decay rate is adjusted relative to the purely leptonic rate to give good agreement with the measured $\tau^\pm$ branching fractions for the particular case of $\tau^\pm$ decay. The simulation of the decay is discussed in detail in Ref. 14.

We simulate $e^+e^- \to Z \to \nu_4\bar{\nu}_4$ for four ν_4 masses: $m_4 = 2.5, 5.0, 10$ and 22 GeV. For each mass, we choose a value for $|U_{\tau 4}|^2$ which results in a ν_4 lifetime long enough to lie in a region of the plane of m_4 versus $|U_{\tau 4}|^2$ which has been previously excluded by a direct search. The simulated cases are indicated as solid dots in Fig. 1. These are the most conservative cases in our search region since the efficiency for the generated signal to pass our selection criteria is always higher for shorter lifetimes (larger values of $|U_{\tau 4}|^2$). The branching fraction of the ν_4 to two charged particles varies from $\approx 87\%$ for $m_4 = 2.5$ GeV to $\approx 28\%$ for $m_4 = 22$ GeV.

We simulate the background from $e^+e^- \to Z \to q\bar{q}$ $(q = u, d, s, c, b)$ with two different models: Lund 6.3 shower[15] and Webber 4.1.[16] All simulated events (including $\nu_4\bar{\nu}_4$) are overlaid with an event from a randomly selected SLC beam crossing to accurately incorporate the effects of beam-related backgrounds in the detector.

To attempt to separate the detected decay products of the ν_4 and $\bar{\nu}_4$, the thrust axis of the event is determined with the charged and neutral particles described above and the event is divided into two hemispheres by the plane perpendicular to this thrust axis. Events are then selected if one hemisphere contains exactly two charged tracks (and any number of neutral particles) and the opposite hemisphere contains at least two charged tracks (2 vs. N, $N \geq 2$). Events are rejected if the magnitude of the cosine of the angle between the beam and the thrust axis $|\cos\theta_{thr}|$ is greater than 0.80.

We now look at the total energy of the charged tracks in the hemisphere with the minimum charged energy, E_{ch}^{min}. The distribution of E_{ch}^{min} peaks near 10 GeV for the simulated ν_4 events and near 1.5 GeV for the simulated $q\bar{q}$ events. A requirement of $E_{ch}^{min} > 6$ GeV rejects approximately half of the $q\bar{q}$ background but rejects only 12% to 25% of the $\nu_4\bar{\nu}_4$ signal, depending on m_4.

The results of applying the three selection criteria described above to the simulated $\nu_4\bar{\nu}_4$ and $q\bar{q}$ events are shown in Table 1. All numbers of events are normalized to the SLC data sample. The results are shown for both the Lund and Webber $q\bar{q}$ Monte Carlos.

If we observe the number of events predicted by the Lund Monte Carlo, we can expect to exclude the signal for the 2.5, 5.0, and 10.0 GeV cases with just the selection criteria described so far, even if we conservatively assume zero expected background. For the $m_4 = 22$ GeV case, however, the expected signal would not be excluded at 95% confidence level if we observe the number of background events predicted by the Lund Monte Carlo and conservatively assume zero expected background.

Therefore, for the high-mass cases ($m_4 \geq 10$ GeV), we select events with high sphericity. When we apply a criteria of sphericity greater than 0.04 for $m_4 \geq 10$ GeV, the expected signal is large ($\gtrsim 5$ events) compared to the expected background (≈ 1 event). (See Table 1.)

We now apply the above selection criteria to the data. The number of events passing everything but the sphericity cut is four. When the sphericity requirement is added only one event passes.

To determine the confidence level at which we exclude a $\nu_4\bar{\nu}_4$ signal for various values of m_4, we first derate the expected signal by 10% to take into account systematic errors such as the statistical error on the Monte Carlo ($\approx 4\%$) and the uncertainty in the integrated luminosity for the SLC data sample ($\approx 5\%$). We then calculate the confidence level at which the decay of the Z to $\nu_4\bar{\nu}_4$ is excluded, given the observed signal, assuming the expected number of background events is zero (the most conservative assumption). With *no* sphericity cut, the observed number of events (four) excludes a $\nu_4\bar{\nu}_4$ signal up to a mass of at least 10 GeV at a confidence level greater than 95%. When the sphericity cut is added, the observation of only one event passing the selection criteria excludes at a confidence level greater than 95% a $\nu_4\bar{\nu}_4$ signal with $m_4 < 22$ GeV down to at least 10 GeV.

Therefore, we exclude at a confidence level greater than 95% the decay of the Z to a pair of fourth-generation, Dirac-type neutral leptons with a decay length less than about 1 cm and a mass between 2.5 and 22 GeV. This excludes a region in a plot of m_4 versus $|U_{\tau 4}|^2$ shown in Fig. 1 as the area lying above the solid dots (regions a and i). This is the first time region i has been excluded through a direct search and the first time region a has been excluded in any analysis. Although the exact numbers in Table 1 apply strictly to the case of coupling of the ν_4 to τ^- only, the conclusions also apply to coupling of the ν_4 to e^- or μ^- since the efficiency for the signal to pass the selection criteria is higher for these cases.

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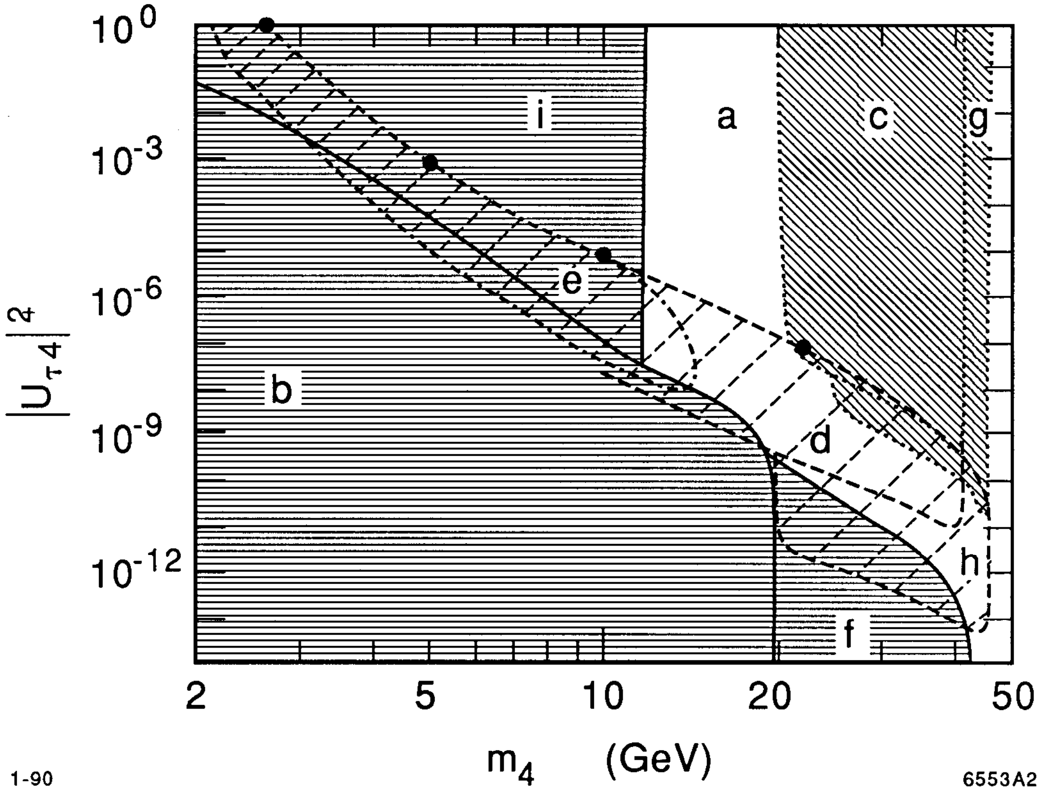
Table 1. Results of applying the selection criteria described in the text to the simulated events. The tabulated numbers represent the number of events expected in the SLC data sample after each additional criteria is applied.

m_4 (GeV)	2.5	5.0	10	22	Lund $q\bar{q}$	Webber $q\bar{q}$
Before cuts	41.2	41.0	40.0	34.7	431	431
2 vs. N, $N \geq 2$	28.5	22.1	16.0	10.6	22.1	28.1
$\lvert\cos\theta_{thr}\rvert < 0.80$	26.3	19.9	13.7	8.9	6.9	12.6
$E_{ch}^{min} > 6$ GeV	23.3	17.2	11.1	6.7	3.0	7.4
Sphericity> 0.04			5.4	6.4	0.9	1.5

FIGURE CAPTION

1) Regions in the plane of m_4 versus $|U_{\tau 4}|^2$ which are excluded at a confidence level of at least 95% for a fourth-generation, Dirac neutrino by this analysis (regions *a* and *i* above the solid dots); by the measurement of the decay width of the Z to invisible final states at SLC[2,3] (region *b*); by a search for high-energy, isolated tracks at SLC[5] (region *c*); by a search for events with a large number of high-impact-parameter tracks at SLC[6] (region *d*) and by a search for events with track vertices detached from the interaction point at PEP[7] (region *e*). The additional regions excluded by the ALEPH collaboration at LEP,[8] but not previously excluded by MARK II, are shown as regions *f, g, h,* and *i.* The shading has the following meaning: horizontal lines indicate regions excluded by measurements of the Z resonance parameters; dashed diagonal lines indicate regions excluded by direct searches for tracks not originating from the collision point; and solid diagonal lines indicate regions excluded by direct searches for events with isolated tracks. The solid dots indicate the cases simulated for this study.



10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
$|U_{\tau 4}|^2$
i
a
c
g
e
b
d
h
f
2
5
10
20
50
m_4 (GeV)
1-90
6553A2

Fig. 1