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Authors
Jung, CK
Van Kooten, R
Abrams, GS
et al.

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Search for Long-Lived Massive Neutrinos in Z Decays

C. K. Jung,[1] R. Van Kooten,[1] G. S. Abrams,[2] C. E. Adolphsen,[3] D. Averill,[4] J. Ballam,[1] B. C. Barish,[5] T. Barklow,[1] B. A. Barnett,[6] J. Bartelt,[1] S. Bethke,[2] D. Blockus,[4] G. Bonvicini,[7] A. Boyarski,[1] B. Brabson,[4] A. Breakstone,[8] F. Bulos,[1] P. R. Burchat,[3] D. L. Burke,[1] R. J. Cence,[8] J. Chapman,[7] M. Chmeissani,[7] D. Cords,[1] D. P. Coupal,[1] P. Dauncey,[6] H. C. DeStaebler,[1] D. E. Dorfan,[3] J. M. Dorfan,[1] D. C. Drewer,[6] R. Elia,[1] G. J. Feldman,[1] D. Fernandes,[1] R. C. Field,[1] W. T. Ford,[9] C. Fordham,[1] R. Frey,[7] D. Fujino,[1] K. K. Gan,[1] C. Gatto,[3] E. Gero,[7] G. Gidal,[2] T. Glanzman,[1] G. Goldhaber,[2] J. J. Gomez Cadenas,[3] G. Gratta,[3] G. Grindhammer,[1] P. Grosse-Wiesmann,[1] G. Hanson,[1] R. Harr,[2] B. Harral,[6] F. A. Harris,[8] C. M. Hawkes,[5] K. Hayes,[1] C. Hearty,[2] C. A. Heusch,[3] M. D. Hildreth,[1] T. Himel,[1] D. A. Hinshaw,[9] S. J. Hong,[7] D. Hutchinson,[1] J. Hylen,[6] W. R. Innes,[1] R. G. Jacobsen,[1] J. A. Jaros,[1] J. A. Kadyk,[2] J. Kent,[3] M. King,[3] S. R. Klein,[1] D. S. Koetke,[1] S. Komamiya,[1] W. Koska,[7] L. A. Kowalski,[1] W. Kozanecki,[1] J. F. Kral,[2] M. Kuhlen,[5] L. Labarga,[3] A. J. Lankford,[1] R. R. Larsen,[1] F. Le Diberder,[1] M. E. Levi,[2] A. M. Litke,[3] X. C. Lou,[4] V. Lüth,[1] J. A. McKenna,[5] J. A. J. Matthews,[6] T. Mattison,[1] B. D. Milliken,[5] K. C. Moffeit,[1] C. T. Munger,[1] W. N. Murray,[4] J. Nash,[1] H. Ogren,[4] K. F. O'Shaughnessy,[1] S. I. Parker,[8] C. Peck,[5] M. L. Perl,[1] F. Perrier,[1] M. Petradza,[1] R. Pitthan,[1] F. C. Porter,[5] P. Rankin,[9] K. Riles,[1] F. R. Rouse,[1] D. R. Rust,[4] H. F. W. Sadrozinski,[3] M. W. Schaad,[2] B. A. Schumm,[2] A. Seiden,[3] J. G. Smith,[9] A. Snyder,[4] E. Soderstrom,[5] D. P. Stoker,[6] R. Stroynowski,[5] M. Swartz,[1] R. Thun,[7] G. H. Trilling,[2] P. Voruganti,[1] S. R. Wagner,[9] S. Watson,[3] P. Weber,[9] A. Weigend,[1] A. J. Weinstein,[5] A. J. Weir,[5] E. Wicklund,[5] M. Woods,[1] D. Y. Wu,[5] M. Yurko,[4] C. Zaccardelli,[3] and C. von Zanthier[3]

[1]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[2]*Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720*
[3]*University of California, Santa Cruz, California 95064*
[4]*Indiana University, Bloomington, Indiana 47405*
[5]*California Institute of Technology, Pasadena, California 91125*
[6]*Johns Hopkins University, Baltimore, Maryland 21218*
[7]*University of Michigan, Ann Arbor, Michigan 48109*
[8]*University of Hawaii, Honolulu, Hawaii 96822*
[9]*University of Colorado, Boulder, Colorado 80309*
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We search for events in the Mark II detector at the SLAC Linear Collider with the topology of a Z boson decaying into a pair of long-lived massive particles. No events that are consistent with the search hypothesis are found. Interpreting the long-lived particle as a sequential Dirac neutrino ν_4 of the fourth generation, we exclude at the 95% confidence level a significant range of mixing-matrix elements of ν_4 to other-generation neutrinos for a ν_4 mass from 10 to 43 GeV/c^2.

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Despite the success of the present three-generation standard model, there is immense interest in looking for new generations of fermions. The standard model itself imposes no restrictions on the number of possible generations or on the masses of the new particles. Motivation to search for long-lived massive particles comes from various theories[1] asserting their existence. Among all possible new particles, a fourth-generation neutrino draws the most immediate attention. If one extends the mass structure of the known fundamental fermions, the neutrino would be the lightest member of a new fourth generation and thus the most accessible to discovery by present experiments. Recently, measurements have been made at the SLAC Linear Collider[2] and the CERN e^+e^- collider LEP[3] to determine the number of neutrino species. The results rule out at 95% confidence level (C.L.) the possibility of a fourth-generation neutrino. These measurements, however, assume the neutrino to be massless and stable.

In this Letter, we present a search for long-lived massive particles in Z-boson decays. The data used in this analysis were obtained with the Mark II detector at the SLAC e^+e^- Linear Collider (SLC) operating in the e^+e^- center-of-mass energy ($E_{\mathrm{c.m.}}$) range from 89.2 to 93.0 GeV. Although the search can be applied to other long-lived particles,[4] we parametrize the results in terms of an hypothesized sequential massive Dirac neutrino ν_4. If such a neutrino exists with its charged-lepton partner

L^-, which we assume is heavier than the neutrino, then the neutrino weak eigenstates ν_l ($l=e$, μ, τ, and L) could be a mixture of the mass eigenstates ν_i ($i=1$–4) in analogy with the quark sector:

$$\nu_l = \sum_{i=1}^{4} U_{li}\nu_i ,$$

where U_{li} is a unitary mixing matrix.

Through this mixing, ν_4 would decay by the weak charged current ($\nu_4 \to l + W^*$, $l=e,\mu,\tau$). Assuming ν_4 mixes with only one other generation of l, the lifetime of the ν_4 can be expressed in terms of the muon lifetime as

$$\tau(\nu_4 \to l^- X^+) = \left(\frac{m_\mu}{m_4}\right)^5 \frac{\tau(\mu \to e\nu\bar{\nu})B(\nu_4 \to l^- e^+ \nu)}{|U_{l4}|^2 f} ,$$

where m_4 is the mass of the neutrino and f is a phase-space suppression factor[5] for massive final-state particles which differs appreciably from unit only when one or more of the final-state particles is a τ lepton or charm quark, and m_4 is relatively small. The predicted branching fraction for $\nu_4 \to l^- e^+ \nu$ is constant ($\sim 11\%$) for most of our mass search range from 10 to 45 GeV/c^2. Although the unitarity of the mixing matrix and e-μ, μ-τ weak universality restrict the allowed mixings,[6] there is a large region where the mixing is of a value such that the decay length of the ν_4 is experimentally observable.

The expected cross section for $\nu_4\bar{\nu}_4$ pair production at the Z peak is very large: $2.9(\beta/4)(3+\beta^2)$ nb, where β is the velocity of the ν_4 in the e^+e^- center-of-mass frame. For a 35-GeV/c^2 ν_4, a total of 24 produced events would be expected in the accumulated Mark II data sample of 19 nb^{-1}.

To search for these particles, we utilize the following characteristics of the event topology. In contrast to the hadronic background from the fragmentation of u, d, s, c, and b ($udscb$) quarks, $\nu_4\bar{\nu}_4$ events with long-lived ν_4 would have detached vertices, and consequently many tracks with large impact parameters with respect to the primary vertex. In addition, since a majority of $\nu_4\bar{\nu}_4$ events are expected to contain one or two hadronic jets, the average charged-particle multiplicity and total visible energy would then be significantly larger than that of the dominant background of beam-gas and beam–beam-pipe interaction events.

A detailed description of the Mark II detector can be found elsewhere.[7] The tracking system of the detector is particularly important for this analysis. The Mark II central drift chamber, based on a six sense-wire cell of jet-chamber configuration, has twelve concentric cylindrical layers at radii between 19.2 and 151.9 cm. The chamber is immersed in a 4.75-kG solenoidal magnetic field and has an intrinsic position resolution of less than 200 μm, resulting in a charged-particle momentum resolution of $\sigma(p)/p^2 = 0.0046$ (GeV/c)$^{-1}$.

In order to ensure good track reconstruction, we require charged tracks to be within the angular region $|\cos\theta| < 0.82$, where θ is the angle with respect to the beam axis, and to have transverse momentum with respect to the beam axis of at least 150 MeV/c. We also require electromagnetic showers to have shower energy greater than 500 MeV and to be within $|\cos\theta| < 0.68$ for the barrel calorimeter and within $0.74 < |\cos\theta| < 0.95$ for the end-cap calorimeters.

The dominant background of beam-gas and beam–beam-pipe interaction events usually are forward scattered, and have low multiplicity and low total energy. To eliminate them, we require an event to have at least eight charged tracks and to have total visible energy greater than 35% of $E_{\rm c.m.}$. In addition, the minimum of energy visible in the forward and backward hemispheres with respect to the electron beam direction must be greater than 7% of $E_{\rm c.m.}$.

To examine the effect of these cuts and to ensure that the remaining events are free of beam-gas and beam–beam-pipe background, we determine the most probable primary vertex of each event in the data sample. When all requirements are applied, there remain no events with primary vertices outside a cylindrical volume centered on the interaction point of radius 1 cm and length 4 cm along the beam axis. The beam pipe has a radius of 3.4 cm. We therefore conservatively estimate that there are less than 0.01 beam-gas and beam–beam-pipe interaction event in our final data sample of 350 events.

The impact parameter b in the plane perpendicular to the beam axis is defined as the distance of closest approach of a charged track to the average beam position. The average beam position for events in a particular time period is defined as the average of the fitted primary vertex positions of the hadronic events in that period. The data are divided into blocks in which there is no evidence of a beam-position movement of more than 200 μm as determined by the SLC final-focus beam-position monitoring systems. Each data block contains more than fifty hadronic events, and the typical error in the average beam position is less than 40 μm in both horizontal and vertical directions. Since the SLC beam size is very small (typically 5 μm in the plane perpendicular to the beam axis), its contribution to the uncertainty in the average beam position is negligible. We therefore assign an error of 200 μm to the measured beam position in each event.

The significance of a charged track's impact parameter is defined as the impact parameter divided by its error σ_b, which is the sum in quadrature of the track-position error perpendicular to the track trajectory (about 300 μm for high-momentum tracks) and the error in the average beam position. An event-search parameter $\chi_{\rm imp}$ is then defined as the fraction of charged tracks with significance b/σ_b greater than 5.0. As seen in Fig. 1, hadronic background events containing charm-, bottom-, or strange-quark decays rarely yield $\chi_{\rm imp}$ greater than 0.5, since there are many other tracks in the

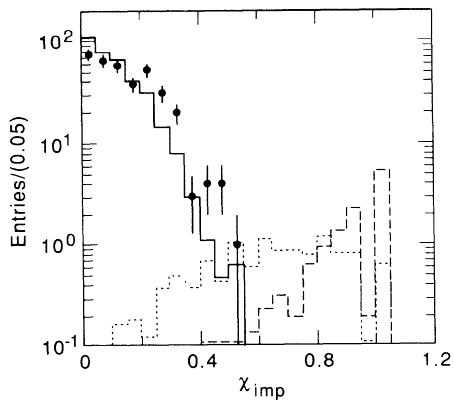

FIG. 1. Distribution of ν_4 search parameter χ_{imp} for data (solid circles with error bars), *udscb* Monte Carlo simulations (solid line), a 35-GeV/c^2 ν_4 with a lifetime of 100 ps (dotted line, normalized to data), and a 35-GeV/c^2 ν_4 with a lifetime of 1000 ps (dashed line, normalized to data).

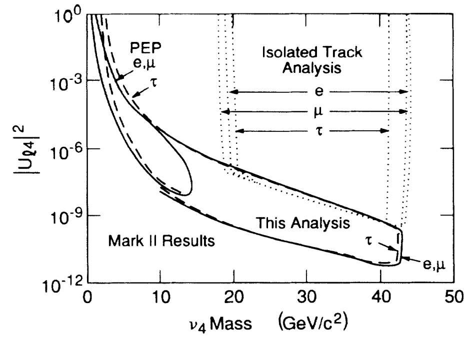

FIG. 2. 95%-C.L. excluded regions for a hypothesized fourth-generation long-lived massive Dirac neutrino ν_4 as a function of mass and mixing-matrix element $|U_{l4}|^2$, $l=e$, μ, or τ. Also shown are the equivalent excluded regions for a Mark II isolated-track search described in Ref. 14, and a Mark II search for detached vertices at PEP described in Ref. 15.

event which project to the primary vertex;[8] however, many $\nu_4\bar{\nu}_4$ events with a reasonable lifetime would yield χ_{imp} greater than 0.5. The data and Monte Carlo *udscb* χ_{imp} distributions disagree somewhat. This discrepancy is mainly due to nuclear interactions of particles which are not fully simulated in the Monte Carlo program.[9] When the estimated 0.3 nuclear interaction per event is taken into account, the distributions are consistent. We therefore demand χ_{imp} of an event to be greater than 0.6 for it to be tagged as a long-lived $\nu_4\bar{\nu}_4$ signal event.

No events in the final data set are tagged as $\nu_4\bar{\nu}_4$ signal events. Monte Carlo *udscb* simulations [LUND 6.3 shower (Ref. 10) and WEBBER 4.1 (Ref. 11)] predict less than 0.2 event to pass all cuts.

In order to interpret the null-search result for $\nu_4\bar{\nu}_4$ events as an excluded region in the m_4-$|U_{l4}|^2$ plane, $\nu_4\bar{\nu}_4$ events are generated with various lifetimes and masses with a Monte Carlo program[12] that simulates the response of the Mark II detector. The number of $\nu_4\bar{\nu}_4$ events expected to be produced N_{ν_4} is normalized to the total number of hadronic events ($N_h=450$) that fulfill the hadronic-event-selection criteria described in a previous Letter:[13]

$$N_{\nu_4}=\frac{N_h\Gamma_{\nu_4}}{\epsilon_q\Gamma_q+\epsilon_{h\nu_4}\Gamma_{\nu_4}},$$

where Γ_q is the partial decay width of the Z to *udscb* quarks, $\epsilon_q=0.953$ is the efficiency for *udscb* quarks to pass the hadronic-event criteria, Γ_{ν_4} is the partial width of the Z to $\nu_4\bar{\nu}_4$, and $\epsilon_{h\nu_4}$ is the efficiency for the $\nu_4\bar{\nu}_4$ events to pass the hadronic-event criteria.

Charged- and neutral-energy trigger emulator programs are applied to simulated $\nu_4\bar{\nu}_4$ events since a long-lived ν_4 might not decay within the detector fiducial volume defined for triggering.[13] Event-selection cuts are applied only to those events that would trigger our data-acquisition system and detection efficiencies ϵ_{ν_4} are determined. As an example, for a 35-GeV/c^2 ν_4 with a mean decay length of 1 m, a trigger efficiency of 90%, and a ϵ_{ν_4} of 15% including trigger efficiency is found. For a 35-GeV/c^2 ν_4 with mean decay length of 5 cm, ϵ_{ν_4} is 45%. Detection efficiencies are equal to one another within errors for $\nu_4\to e+W^*$ and $\nu_4\to\mu+W^*$ but are about 10% lower for $\nu_4\to\tau+W^*$.

Uncertainties in detection efficiency from Monte Carlo statistics ($\approx 2\%$), detector simulation and beam backgrounds ($\approx 4\%$), tracking efficiencies for tracks with large impact parameters ($\approx 10\%$), and different fragmentation models ($\approx 1\%$) are estimated. Uncertainties in the number of produced events arise from the statistical error in N_h and from small errors in ϵ_q and $\epsilon_{h\nu_4}$. The total error is calculated by summing the individual statistical and systematic errors in quadrature.

Detection efficiencies are determined for $\nu_4\bar{\nu}_4$ events for a grid of values in the m_4-$|U_{l4}|^2$ plane. Two-dimensional polynomial interpolation is used to find efficiencies between grid points. The expected number of $\nu_4\bar{\nu}_4$ events after all cuts is then determined, and reduced by the total error described above to obtain a conservative 95%-C.L. contour in the m_4-$|U_{l4}|^2$ plane. The results are shown in Fig. 2. The upper and lower boundaries of the contour at a mass of 35 GeV/c^2 correspond to mean decay lengths of 0.6 and 83 cm, respectively. Also shown in Fig. 2 are the region excluded by an isolated-track search in the same data sample,[14] and the region excluded by the Mark II experiment at the SLAC storage ring PEP.[15]

In conclusion, we observe no events that are consistent with the search hypothesis of a sequential long-lived massive Dirac neutrino. We significantly extend the excluded region at 95% C.L. in the m_4-$|U_{l4}|^2$ plane determined by lepton universality,[6] and other experiments;

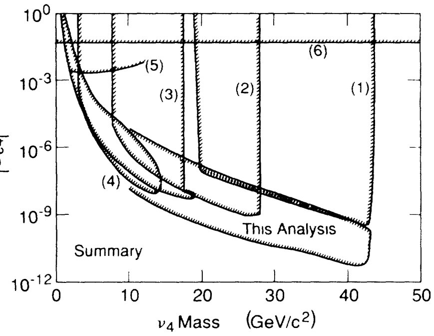

FIG. 3. 95%-C.L. excluded regions for a hypothesized fourth-generation long-lived massive Dirac neutrino ν_4 as a function of mass and mixing-matrix element $|U_{e4}|^2$ for the present analysis compared to those obtained by (1) Mark II, Ref. 14; (2) AMY, Ref. 16; (3) CELLO, Ref. 17; (4) Mark II detached vertex search at PEP, Ref. 15; (5) monojet searches at PEP, Ref. 18; and (6) e-μ universality, Ref. 6.

most recently by the AMY Collaboration,[16] and CELLO Collaboration,[17] and monojet searches at PEP.[18] The results are summarized in Fig. 3 for $l=e$. The excluded regions are very similar for $l=\mu$. It is interesting to note that, whereas most other searches are restricted to limiting $|U_{e4}|^2+|U_{\mu4}|^2$, this search also limits $|U_{\tau4}|^2$. Finally, it should be noted that the described search procedure is also valid for any general long-lived particles decaying into many particles.

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