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Search for Excited Neutrinos in Z Decay

The ALEPH Collaboration

Abstract

Excited neutrinos decaying into a neutrino and a photon are searched for in the ALEPH detector at LEP. No evidence is found for Z decays into $\bar{\nu}\nu^*$ or $\bar{\nu}^*\nu^*$ final states. Upper limits are derived on excited neutrino couplings up to excited neutrino masses close to the Z mass. Lower limits on the ν^* mass, independent of the ν^* decay modes, are deduced from the total Z width.

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1 Introduction

The existence of charged excited leptons, ℓ^* , with masses below $M_Z/2$ has already been excluded by data taken at the Large Electron Positron storage ring, LEP, at CERN, [1,2,3]. This lower limit has been extended up to M_Z for $Z\ell\ell^*$ coupling constants as low as a few 10^{-3} GeV^{-1} .

Similar limits on excited neutrinos do not yet exist, although composite models of leptons [4] foresee weak couplings between vector bosons and excited neutrinos, ν^* . LEP opens new possibilities of searching for ν^* in Z decays and thus of setting limits on $Z\nu^*\nu^*$ and $Z\nu^*\nu$ couplings for the first time.

In this paper a direct search for ν^* production is performed via its $\nu^* \rightarrow \nu\gamma$ decay using the capability of ALEPH to detect purely photonic final states. The limits obtained from the measured width of the Z are also presented.

If the ν^* has Standard Model couplings, the $e^+e^- \rightarrow \nu^*\bar{\nu}^*$ cross section at the Z peak can be accurately predicted; it is a few nanobarns at low masses and is restricted by the available phase space as the mass increases. Precise measurements of the Z total width rule out this process, independently of the ν^* decay, up to certain masses. However with the present ALEPH integrated luminosity, $L = 3.67 \text{ pb}^{-1}$, a direct search for two photon events enables much smaller coupling constants to be investigated.

Z decays into single excited neutrino final states, $Z \rightarrow \nu^*\bar{\nu}$ or $\nu\bar{\nu}^*$, depend on the strength of the $Z\nu\nu^*$ coupling generally expressed as λ_Z/m^* , where m^* is the excited neutrino mass, or in terms of the compositeness energy scale $\Lambda = m^*/\lambda_Z$. The total integrated luminosity quoted above makes ALEPH sensitive to cross sections as low as a few picobarns, therefore to single excited neutrino production up to ν^* masses close to the phase space limit, $m^* = M_Z$, and this for a compositeness energy scale up to 2.5 TeV (i.e. a coupling constant λ_Z/m^* down to $4 \times 10^{-4} \text{ GeV}^{-1}$) [5].

Radiative decays of excited neutrinos, $\nu^* \rightarrow \nu\gamma$, are natural for such composite objects, even if other decay modes, via $\nu^*\nu Z$ and $\nu^*\ell W$ couplings, could also occur [6]. Therefore a search was made for final states with one or two high energy photons and missing energy. In the single excited neutrino mode, the expected photon energy spectrum is rather flat from a minimum energy $k_{\min} = m^{*2}/2M_Z$ to a maximum, $k_{\max} = M_Z/2$ ($= 45.6 \text{ GeV}$). As an example, if $m^* = M_Z/2$, $k_{\min} = 11.4 \text{ GeV}$, and this enables all backgrounds to be reduced to a very low level. The main possible backgrounds are the radiative neutrino pair production, $e^+e^- \rightarrow \gamma Z \rightarrow \gamma\nu\bar{\nu}$, radiative Bhabha events, $e^+e^- \rightarrow \gamma(e^+e^-)$ where the electron and positron are both undetected, and the reaction $e^+e^- \rightarrow \gamma(\gamma\gamma)$, where only one (radiative) photon is detected. For all three of these radiative processes, the photon energy distribution is peaked at very low energies.

The only physical background to the two photon mode comes from the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$. Such events may be removed by simple kinematical cuts due to their peculiar topology – two photons emitted back to back with energies close to the beam energy.

2 The ALEPH detector

ALEPH has already been described in detail elsewhere [7]. The analysis presented here relies entirely on the electromagnetic calorimeter ECAL. The central tracking device, TPC, is used only to veto events with charged particles.

The ECAL is made of a lead/wire tube sandwich and is placed inside the solenoid. The barrel part is divided into twelve modules, each covering a 30° angle in azimuth. The two end caps are also divided into twelve modules. The polar angle coverage is thus complete down to 11° with respect to the beam axis. The total thickness corresponds to 22 radiation lengths at normal incidence. The longitudinal sampling consists of 2 mm lead layers in the 13 first radiation lengths (33 layers), and 4 mm lead layers in the last 9 radiation lengths (12 layers). Anode wire signals are summed plane by plane, giving 45 read-out channels per module and 1 620 channels for the whole calorimeter. In addition, for each module, wire signals are summed over the 45 planes. A sampling, every 512 ns, during the rise time of these signals leads to a measurement of the interaction time t_0 of particles in ECAL, with a resolution which varies from 50 ns at 500 MeV to 20 ns at 45 GeV. The collected charges are induced on cathode planes, segmented in approximately $3 \times 3 \text{ cm}^2$ copper pads, which correspond roughly to the lateral size of electromagnetic showers. Pads from consecutive planes are connected together to form "towers" pointing to the interaction region. Each tower is segmented into three "storeys" in depth, corresponding to the three ECAL stacks of 4, 9 and 9 radiation lengths respectively. There are 49 512 towers in the barrel and 24 576 in the end caps, giving a total of 221 184 read-out channels.

The electromagnetic calorimeter is extended at low angles, down to 50 mrad with respect to the beam axis, by a smaller calorimeter, LCAL, devoted to the luminosity measurement by detecting forward Bhabha scattering events. Its structure is similar to that of the main calorimeter ECAL with both anode and cathode read-out. It is used in this analysis as a veto against radiative Bhabha events.

The relevant trigger for single and double high energy photon events is an ECAL energy trigger which requires at least 6.5 GeV in the barrel. It is based on a coincidence between the total sums of odd and even wire planes with at least 3.25 GeV in each of them. This analysis uses only the barrel part of ECAL since the background from radiative Bhabha scattering is very much higher in the end caps.

3 Event analysis and background rejection

3.1 Event selection

Data collected at several energies across the Z peak from $\sqrt{s} = 88.25 \text{ GeV}$ to $\sqrt{s} = 95 \text{ GeV}$, with all relevant subdetectors operational, were processed through the standard ALEPH acquisition and reconstruction programs. Events are selected as photon candidates when satisfying the following conditions:

- no reconstructed charged track with more than three TPC hits and a momentum larger than 500 MeV/c;
- one (single photon case) or two (two photon case) ECAL barrel modules with wire energy, E_W , larger than 5 GeV;
- no other ECAL module with wire energy larger than 200 MeV (the r.m.s. electronic noise is about 20 MeV);
- the measured event time, t_0 , must coincide with the beam crossing time within ± 100 ns. Figure 1 shows the t_0 distribution for single photon candidates. Beam related events are peaked near $t_0 = 0$ ns with a resolution of 15 ns; background events such as cosmic rays and detector noise (sparks, radioactive nuclei decays in the electromagnetic calorimeter) are randomly distributed. The slightly decreasing slope is a trigger effect: electric charges are integrated and sampled for trigger purpose at a constant time ($3.5 \mu\text{s}$) after the bunch crossing, so that the percentage of collected charges which are integrated decreases as their true occurrence time increases with respect to the bunch crossing;
- for each fired module, the sum of tower energy, E_T , is compared to the sum of wire energy, E_W , and the ratio E_W/E_T must lie between 0.6 and 1.3. In addition the tower energy must arise from only one main cluster with possible small nearby clusters.

3.2 Photon identification

Two additional criteria are now applied to photon candidates, to remove non-electromagnetic residual background, as well as photons and neutral pions produced in beam-gas interactions:

- transverse compactness – the energy deposited in the four leading towers of the main cluster must be larger than 70% of the tower energy E_T ;
- vertex – two barycenters are reconstructed, one in the first stack of ECAL, one in the second stack. The z and ϕ coordinates are derived from a simple centroid method using storey energies, while depth coordinates are determined from the longitudinal wire profile in each stack. This leads to the line of flight of the photon candidate and its closest approach to the beam line, considered as the vertex where the photon originates. The vertex coordinate along the beam direction is required to correspond to the geometrical interaction point within ± 60 cm.

The overall efficiency due to event selection and photon identification has been checked on both simulated events and a reference sample of photons coming from real $e^+e^- \rightarrow \gamma\gamma$, $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ events. Energies of identified photons lie in the range 5 GeV to 45 GeV, which is the expected range for photons from ν^* decays. The efficiency is found to be $\epsilon_\gamma = 85 \pm 2\%$ with a loss of 8% from identification algorithms, 2% from dead zones between ECAL barrel modules, and 5% due to photon conversions in material in front of the TPC.

Distributions of transverse compactness and longitudinal vertex position are shown on figures 2a and 2b, respectively, for the reference sample and the single photon candidates.

3.3 Single photon search

In order to avoid trigger threshold effects, the wire energy E_w is required to be greater than 7 GeV. Only 10 events survive the event selection and photon identification. For 7 of them, an energy deposit of at least 25 GeV is recorded on both towers and wires of a LCAL module. These 7 events are consistent with $e^+e^-\gamma$ or $\gamma\gamma\gamma$ final states, in which electrons or photons detected in LCAL balance the transverse momentum of the photon emitted in the barrel part of ECAL. From randomly triggered events, the probability per bunch crossing of observing such LCAL energies is found to be 0.1%. Three single photon candidates remain.

Background has been simulated using event generators for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ [8], $e^+e^- \rightarrow e^+e^-\gamma$ [9] and $e^+e^- \rightarrow \gamma\gamma\gamma$ [10] reactions. The standard ALEPH simulation and reconstruction programs are applied to generated events, followed by the event selection and analysis described above. For a luminosity $L = 3.67 \text{ pb}^{-1}$, the expected numbers of events from the 3 reactions are 2.1, 3.2 and 0.6 respectively. The total expected number of background events, 5.9, is statistically consistent with the 3 observed events. This corresponds to an upper limit of 4.4 single excited neutrino events at a 95% confidence level.

3.4 Double photon search

The number of events with two identified photons is 51. These events are consistent with the expectation from the reaction $e^+e^- \rightarrow \gamma\gamma(\gamma)$. All are rejected by requiring that the sum of the energies of the two photons be less than 75 GeV and that their acoplanarity be greater than 0.5° . The cuts produce negligible loss of efficiency for $\nu^*\bar{\nu}^*$ detection. No event compatible with the reaction $e^+e^- \rightarrow \nu^*\bar{\nu}^*$ is left. The expected residual background is estimated using the $e^+e^- \rightarrow \gamma\gamma(\gamma)$ generator of ref.[10]. It is found to be 0.5 event, so that the 95% CL upper limit for excited neutrino pairs is 3 events.

4 Limits on excited neutrino production

4.1 Single excited neutrino production

A single excited neutrino is assumed to be produced via the magnetic $Z \nu^* \nu$ coupling described by an effective Lagrangian of the form:

$$\mathcal{L} = \frac{e\lambda_Z}{2m^*} \bar{\psi}(\nu^*) \sigma^{\mu\nu} (1 - \gamma^5) \psi(\nu) F_{\mu\nu}^Z + h.c.$$

The resulting differential cross section for reaction $e^+e^- \rightarrow \nu^*\bar{\nu}$ is given by

$$\frac{d\sigma}{dt} = \frac{\alpha G_\mu}{2\sqrt{2}} \left(\frac{\lambda_Z}{m^*} \right)^2 \frac{M_Z^2}{s} |D_Z(s)|^2 \times$$

$$\left\{ (v_e^2 + a_e^2) [m^{*2}(s - m^{*2}) + 2tu] + 2v_e a_e m^{*2}(t - u) \right\} ,$$

where

- s, t, u are the usual Mandelstam variables,
- M_Z and $D_Z(s)$ are the Z mass and propagator,
 $|D_Z(s)|^2 = 1/[(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]$,
- v_e and a_e are the standard vector and axial vector electron couplings,
 $v_e = -1 + 4 \sin^2 \theta_W$, $a_e = -1$,
- α and G_μ are the electroweak coupling constants.

The only free parameters in this expression are the excited neutrino mass, m^* , and the $Z\nu\nu^*$ coupling constant, λ_Z/m^* . For the $\bar{\nu}^*\nu$ final state, the variables t and u are interchanged.

The excited neutrino then decays into a photon and a massless neutrino. The branching ratio $b(\nu^* \rightarrow \nu\gamma)$ depends on the coupling λ_γ/m^* which is unknown and therefore the predicted single-photon cross section is proportional to $(\lambda_Z/m^*)^2 \cdot b(\nu^* \rightarrow \nu\gamma)$.

To estimate the expected number of single photons, we have generated events according to the above formula at several values of m^* mass. The overall acceptance, $\Omega_\gamma = 67\%$, including the photon efficiency ϵ_γ , is deduced from event simulation, reconstruction, selection and analysis. No radiative effects are included in the generator but the cross sections are corrected for initial state radiation at each value of $\sqrt{s}$ and m^* . The expected number of events for a given mass m^* is calculated combining all energies and luminosities, and compared to the 95% CL experimental upper limit of 4.4 events.

Figure 3 shows for instance the corresponding lower limit, $m^* > 74.7 \text{ GeV}/c^2$, assuming the branching ratio $b(\nu^* \rightarrow \nu\gamma)$ to be 100%, and a coupling constant λ_Z/m^* equal to $4 \times 10^{-4} \text{ GeV}^{-1}$, i.e. a compositeness energy scale of 2.5 TeV. Varying the coupling constant λ_Z/m^* and the branching ratio b , a region of the plane $(\lambda_Z/m^*) b^{1/2}$ versus m^* is excluded at a 95% confidence level. As it can be seen on figure 4a, the upper limit on the quantity $(\lambda_Z/m^*) b^{1/2}$ is $\sim 2 \times 10^{-4} \text{ GeV}^{-1}$ up to an excited neutrino mass close to the Z mass. It is reduced by a factor $\sqrt{3}$ if we assume excited lepton universality for three mass-degenerate families.

The experimental limit of 4.4 single excited neutrino events also provides an upper limit of the product of $Z \rightarrow \nu^*\nu$ and $\nu^* \rightarrow \nu\gamma$ branching ratios. Taking into account the total number of Z 's produced and the overall photon acceptance, which is independent of the ν^* mass, this limit is :

$$b(Z \rightarrow \nu^*\nu) b(\nu^* \rightarrow \nu\gamma) < 6 \times 10^{-5} \text{ at 95\% CL.}$$

4.2 Double excited neutrino production

According to current models, the production of pairs of excited leptons is independent of the compositeness scale [4] and therefore the $Z\nu^*\nu^*$ coupling is large. The $Z \rightarrow \nu^*\bar{\nu}^*$ width is parametrized by the formula

$$\Gamma = \frac{G_\mu}{24\pi\sqrt{2}} M_Z^3 \beta \left[\frac{1}{2} (3 + \beta^2) (g_L^2 + g_R^2) + 3(1 - \beta^2) g_L g_R \right]$$

where β is the velocity of the excited neutrino and g_L and g_R are the left- and right-handed $Z\nu^*\bar{\nu}^*$ couplings.

We have considered three cases :

- the Dirac neutrino: $g_L = 1, g_R = 0$,
- the Majorana neutrino: $g_L = -g_R = 1/\sqrt{2}$, where the factor $1/2$, which accounts for the identity of two final neutrinos, is included into the couplings,
- the model of Hagiwara et al [5], which assumes the existence of left- and right-handed excited lepton doublets with the same $SU(2) \times U(1)$ quantum numbers, and predicts $g_L = g_R = 1$.

For a very light excited neutrino, the two first cases are indistinguishable and identical to ordinary neutrinos, whereas the Hagiwara model predicts the $Z \rightarrow \nu^*\bar{\nu}^*$ width two times larger than the Standard Model value for $Z \rightarrow \nu\bar{\nu}$. Given such abundance, a large range of excited neutrino mass can be excluded merely from the total Z width, irrespective of the ν^* decay modes.

The limit on the ν^* mass is obtained by attributing to the $\nu^*\bar{\nu}^*$ decay channel the excess of the measured total Z width over the Standard Model prediction. The upper limit of the excess, $\Delta\Gamma$, is

$$\Delta\Gamma = \Gamma_{\text{meas}} + \Delta\Gamma_{\text{meas}} - \Gamma_{\text{SM}} + \Delta\Gamma_{\text{SM}}$$

The Z width $\Gamma_{\text{meas}} = (2497 \pm 31)$ MeV has been determined by fitting the Z line shape [11]. $\Delta\Gamma_{\text{meas}} = 1.64 \times 31$ MeV = 51 MeV is one-sided 95% confidence level deviation. The Standard Model width $\Gamma_{\text{SM}} = 2475$ MeV is the lower limit of the theoretical expectation and therefore it is calculated assuming a light top quark ($m_t = 90$ GeV/c²) and a heavy Higgs ($m_H = 1000$ GeV/c²) [12]. The error $\Delta\Gamma_{\text{SM}} = 17$ MeV corresponds to the uncertainty of the strong coupling constant α_s [13]. Hence the maximum allowed value of the $Z \rightarrow \nu^*\bar{\nu}^*$ width is:

$$\Delta\Gamma = 89 \text{ MeV.}$$

$\Delta\Gamma$ is compared with the predictions of the three models, assuming in each case either one excited neutrino, or three mass-degenerate excited neutrino species.

The excluded region of the ν^* mass extends from 0 to the value given in table 1.

	1 ν^*	3 ν^*
Dirac	35.4	44.3
Majorana	26.6	37.7
Hagiwara et al.	44.8	45.5

Table 1: Upper limits of excluded ν^* mass region in GeV/c².

The direct search for two-photon final states provides a limit on the production of a pair of excited neutrinos each decaying into a photon. The expected number of such events is compared to the experimental upper limit of 3 events. The detection efficiency is determined by simulating the reaction kinematics and the detector response and applying the selection criteria. The models predict the ν^* angular distribution in the form $1 + B \cos^2 \theta$ with $0 < B < 1$ depending of the ν^* mass. We have chosen the most pessimistic case, $B = 1$. The ν^* decay is assumed to be isotropic. The detection efficiency is found to be about 40% for all ν^* masses.

An upper limit at 95% confidence level is deduced for the product of the branching ratios.

$$b(Z \rightarrow \nu^* \bar{\nu}^*) b^2(\nu^* \rightarrow \nu \gamma) < 7 \times 10^{-5}$$

To a large extent, this result is model independent and holds for the production of a pair of heavy neutral objects decaying into a photon and a light invisible particle.

The obtained limit can be interpreted in terms of a model which assumes that the decay $Z \rightarrow \nu^* \bar{\nu}^*$ goes via a coupling f times smaller than the Standard Model coupling for a massive Dirac-type neutrino. The expected number of events is calculated as a function of the factor f . Radiative corrections are taken into account. An upper limit for the quantity $f \times b(\nu^* \rightarrow \nu \gamma)$ is derived as a function of the ν^* mass. Figure 4b shows the excluded region for one and three mass-degenerate excited neutrino families. If the ν^* decay is purely radiative, then the $Z\nu^*\nu^*$ coupling cannot exceed 3.5% of the Standard Model value up to ν^* masses close to $M_Z/2$. This limit is decreased to 2% for three mass-degenerate families.

5 Conclusion

The existence of excited neutrinos with couplings identical to those of the ordinary neutrinos is excluded by the measurement of the Z total width for ν^* mass up to 35.7 GeV/c² for the Dirac-type neutrino and up to 26.9 GeV/c² for the Majorana one. If three mass-degenerate excited neutrinos exist, they are heavier than 44.3 GeV/c² and 37.7 GeV/c², respectively. In the model of Ref.[5] assuming the existence of right-handed excited lepton doublets, both limits are close to 45 GeV/c². These results are independent of the ν^* decay mode.

From the direct search for two-photon final states, the decay $Z \rightarrow \nu^* \bar{\nu}^*$ followed by radiative ν^* decay is excluded at 95% confidence level for a product of branching ratios $b(Z \rightarrow \nu^* \bar{\nu}^*) b^2(\nu^* \rightarrow \nu \gamma)$ greater than 7×10^{-5} . Limits for excited neutrinos are also given for couplings smaller than the Standard Model values for Dirac-type neutrinos, assuming either one or three mass-degenerate flavours.

From the search for single photon final states typical of Z decays into $\nu^* \bar{\nu}$ or $\nu \bar{\nu}^*$, the product of branching ratios $b(Z \rightarrow \nu^* \bar{\nu}) b(\nu^* \rightarrow \nu \gamma)$ greater than 6×10^{-5} is excluded at 95% confidence level. The corresponding upper limit on the $Z\nu\nu^*$ coupling constant $(\lambda_Z/m^*) b^{1/2}(\nu^* \rightarrow \nu \gamma)$ is 2×10^{-4} for excited neutrino mass up to values close to the Z mass. This limit is lower by a factor $\sqrt{3}$ if there were three excited neutrino species.

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Figure Captions

Figure 1. Event time distribution compared to bunch crossing time for single photon candidates.

Figure 2a. Transverse compactness distribution, defined as the fraction of energy in the four leading towers of the electromagnetic cluster, for reference sample of photons from $e^+e^- \rightarrow \gamma\gamma$, $e^+e^-\gamma$, $\mu^+\mu^-\gamma$ events, and for single photon candidates.

Figure 2b. Longitudinal vertex distribution for reference sample of photons from $e^+e^- \rightarrow \gamma\gamma$, $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ events, and for single photon candidates. Events lying outside the range from -60 cm to $+60$ cm are photons or neutral pions produced in beam gas interactions.

Figure 3. Number of expected events from $e^+e^- \rightarrow \nu^*\bar{\nu}$ and $\nu\bar{\nu}^*$ process as a function of excited neutrino mass, m^* , for the following conditions: integrated luminosity $L = 3.67 \text{ pb}^{-1}$, $Z\nu\nu^*$ coupling constant $= 4 \times 10^{-4} \text{ GeV}^{-1}$, branching ratio $b(\nu^* \rightarrow \nu\gamma) = 1$. The 95% CL limit $n_{\text{exp}} = 4.4$ leads to a lower limit, $m^* > 74.7 \text{ GeV}/c^2$.

Figure 4a. Region excluded at a 95% confidence level in the plane $\frac{\lambda_2}{m^*} b^{\frac{1}{2}}(\nu^* \rightarrow \nu\gamma)$ versus m^* . The two limits correspond to a single excited neutrino family and to three mass-degenerate excited neutrino species.

Figure 4b. Region excluded at 95% confidence level in the plane $f \times b(\nu^* \rightarrow \nu\gamma)$ versus m^* . The two limits correspond to a single excited neutrino family and to three mass-degenerate excited neutrino species.

Fig.1

Fig.2a

Fig.2b

Fig.3

Fig. 4a

Fig. 4b