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Search for excited leptons at 161–172 GeV

The ALEPH Collaboration

Abstract

A search for the radiative decay of excited leptons, ℓ^* and ν^*, and for the weak decay of excited electron neutrinos, ν_e^*, was undertaken using the 21.8 pb^{-1} of data collected by ALEPH at 161–172 GeV, No evidence for a signal was found in single or pair production. Excluded mass limits from pair production are close to 85 GeV/c^2 for excited charged leptons and 80.5 GeV/c^2 for excited neutrinos. Limits on the couplings, $\lambda/m_{\ell*}$, of excited leptons were derived from single production. For an excited lepton mass of 150 GeV/c^2, these limits are 0.0004, 0.007, 0.01 and 0.015 GeV^{-1}, for e*, μ^*, τ^*, and $\nu_{\mu,\tau}^*$ respectively. For ν_e^* the limit is below 0.007 GeV^{-1} for masses up to 150 GeV/c^2, independently of the branching ratios of the decays.

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1 Introduction

Excited leptons arise naturally in models where the standard leptons are composite rather than elementary particles [1]. Their masses are determined by the compositeness scale and, if this is not too high, their production at LEP energies may be possible. As LEP reaches new, higher energies searches for such particles must be renewed: this paper describes searches essentially similar to those in [2] at 130–136 GeV. Only excited leptons, ℓ^*, with spin 1/2 and isospin 0 or 1/2 were considered. (Other cases have been discussed in Ref. [3]). If the excited states acquire mass above the electroweak breaking scale (accounting for the rather large masses inferred from their non-appearance at lower energies), they arise as left- and right-hand doublets. The alternative is to assume a chirality structure identical to that of the ground state leptons. As the latter is a more conservative choice, leading to lower production cross-sections, limits will be derived for this particular case.

At LEP, excited leptons can be produced singly ($e^+e^- \to \ell\ell^*$), or in pairs ($e^+e^- \to \ell^*\bar{\ell}^*$). For single production, the effective Lagrangian is given by [1]

$$\mathcal{L}_{\text{eff}} = \sum_{V=\gamma,Z,W} \frac{e}{\Lambda}\bar{\ell}^*\sigma^{\mu\nu}(c_{V\ell^*\ell} - d_{V\ell^*\ell}\gamma^5)\ell\partial_\mu V_\nu + h.c.$$

The precision $g-2$ measurements imply $|c_{\gamma\ell^*\ell}| = |d_{\gamma\ell^*\ell}|$ and the absence of electric dipole moments requires $c_{\gamma\ell^*\ell}$ and $d_{\gamma\ell^*\ell}$ to have the same phase [1, 4]. In the model in [1] all the couplings are assumed to satisfy $c_{V\ell^*\ell} = d_{V\ell^*\ell}$ and can be written:

$$\begin{aligned}
c_{\gamma e^* e} &= -\frac{1}{4}(f + f') \\
c_{\gamma \nu^* \nu} &= \frac{1}{4}(f - f') \\
c_{Z e^* e} &= -\frac{1}{4}(f\cot\theta_W - f'\tan\theta_W) \\
c_{Z \nu^* \nu} &= \frac{1}{4}(f\cot\theta_W + f'\tan\theta_W) \\
c_{W \nu^* e} &= \frac{f}{2\sqrt{2}\sin\theta_W}
\end{aligned}$$

The independent parameters in the model are f/Λ and f'/Λ. By choosing a particular relationship between f and f', only one free parameter multiplying the cross-section remains; λ/m_{ℓ^*}, defined as $f/\sqrt{2}\Lambda$. The scale, Λ, need not be the same for the different lepton flavours.

For pair production, couplings of the same form as in the Standard Model are assumed, the contributions from the above magnetic couplings being expected to be much smaller [5]. Standard Model lepton-pair cross-sections are modified only by velocity factors that correspond to the larger masses of the ℓ^*. The possibility of a form-factor [6] multiplying the standard couplings is also considered.

The presence of magnetic couplings allows the excited leptons to decay to their ground state partners with emission of a vector boson. Branching ratios are calculated according to [6]. For excited charged leptons, $f = f' = 1$ was assumed. For ℓ^* masses below the W and Z, the branching ratio for the radiative decay, $\ell^* \to \ell\gamma$, is virtually 100%. For larger ℓ^* masses the decay channels involving W and Z open up, and for an ℓ^* of mass 140 GeV/c^2 the photonic decay branching ratio is reduced to 43%. The radiative decay of excited neutrinos is allowed only if $f \neq f'$: for the case $f' = 0$ and $f = 1$ the branching ratio for the photonic decay drops to 14% for a 140 GeV/c^2 ℓ^* mass while that of the charged current decay increases to 66%.

All the data taken by the ALEPH detector [7, 8] in the high energy runs in 1996 were used to search for excited leptons. The centre of mass energies were 161.3, 164.5, 170.3 and 172.3 GeV, with corresponding integrated luminosities of 11.08, 0.04, 1.11 and 9.54 pb^{-1}.

2 Excited charged leptons decaying radiatively

Event topologies were one, two, four or six charged tracks, with no net charge for the multi-track cases, plus one or two photons which may include identified pair conversions. In all channels the default selection cuts required the polar angles of all identified charged tracks and photons to be greater than 18.2° and the charged track momenta to be greater than 0.2 GeV/c. The principle background for radiative decays is electroweak and for these Monte Carlo samples five times as large as the data for e*, and fifty times the data for μ^* and τ^* were used.

2.1 Pair production

Excited charged lepton pair production is dominated by s-channel γ or Z exchange. The production rates were thus similar to those for standard, but heavy, leptons, and the radiative decay modes lead to a characteristic topology, $\ell^+\ell^-\gamma\gamma$. The standard model background from lepton pair production with final state radiation can be efficiently reduced by imposing isolation cuts on the photons.

Events with two identified photons with energy exceeding 8 GeV and either two, four or six tracks were selected. In four-track events, there had to be one τ candidate, defined as a track triplet with an invariant mass below the τ mass. In six-track events there had to be two tau track triplets. The photons were required to be isolated from all charged tracks by at least 25°. Tracks and photons were rescaled using energy and momentum conservation [9]. The six candidate data events are shown in Fig. 1. The final cut, based on the expected symmetry of the particle pair required that, when track-photon invariant mass combinations were calculated, there had to be a combination such that the difference between the masses constructed was less than 10 GeV/c^2, which easily exceeds 2σ of the invariant mass resolution even in the τ^* case. None of the data events selected passed this final cut.

Backgrounds were studied using standard electroweak generators, with full detector simulation. Before(after) the cut on mass differences six(zero) events were observed in data where 3.7(1.1) events were expected from background comprising 1.9(0.6) $e^+e^-\gamma\gamma$, 1.0(0.3) $\mu^+\mu^-\gamma\gamma$, 0.7(0.2) $\tau^+\tau^-\gamma\gamma$ and 0.1(0.0) events from other Standard Model processes. Signal events were generated using the KORALZ [10] program modified to produce $\ell^*\bar{\ell}^*$ pairs decaying radiatively and fully simulated in the ALEPH detector Monte Carlo. Over most of the mass-range $45 - 86$ GeV/c^2 the efficiency was 60% for $e^*\bar{e}^*$, 63% for $\mu^*\bar{\mu}^*$ and 51% for $\tau^*\bar{\tau}^*$.

With no events observed, 95% C.L. mass limits were set as shown in Fig. 2(a). Excited states with masses up to 84.7 GeV/c^2 for e*, 84.8 for μ^* and 84.5 GeV/c^2 for τ^* are excluded at 95% confidence level for the case where the form-factor is unity. For masses below these, the 95% C.L. excluded form-factor limit is shown in Fig. 2b.

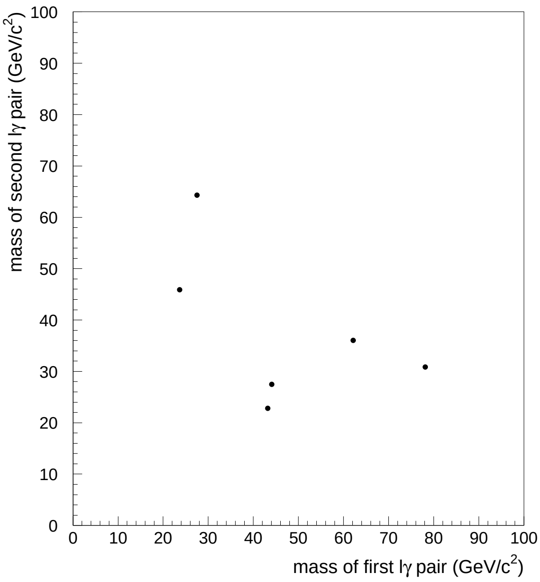

Figure 1: The pairs of ℓ^* masses with the smallest mass differences for the six candidate events in data.

2.2 Single production ($\ell\ell\gamma$ channel)

Excited charged leptons can also be produced singly, in association with their ground state partner. Masses close to the centre of mass energy can be probed this way, but the production cross-section now involves the magnetic coupling, the magnitude of which is unknown. For all flavours, the production can take place *via* s-channel γ or Z exchange.

In single production, the final state usually consists of two leptons and a photon, but for excited electrons, quasi-real Compton scattering largely dominates the production cross-section. Since the spectator electron remains undetected in the beam pipe, the apparent topology, only one electron and a photon, is different. A dedicated analysis has therefore been performed for excited electrons in this configuration, as described in section 2.2.1.

The small amount of luminosity collected at energies well above the Z peak does not allow any improvement to be expected with respect to the LEP1 results for excited lepton masses smaller than 85 GeV/c^2. Therefore the selection criteria were optimized for larger masses.

To qualify, an event had to consist of a dilepton pair (two tracks or one track and a tau-candidate triplet or two triplets) and one isolated photon of energy above the lower kinematic limit for a signal of mass 85 GeV/c^2. This corresponds to a photon energy of about 20 GeV. The isolation criterion for photons was the same as in the previous section. Channel identification was primarily through the standard Aleph algorithms [8] for electrons and muons, but made use also of the larger average net transverse momentum, p_t, in tau events.

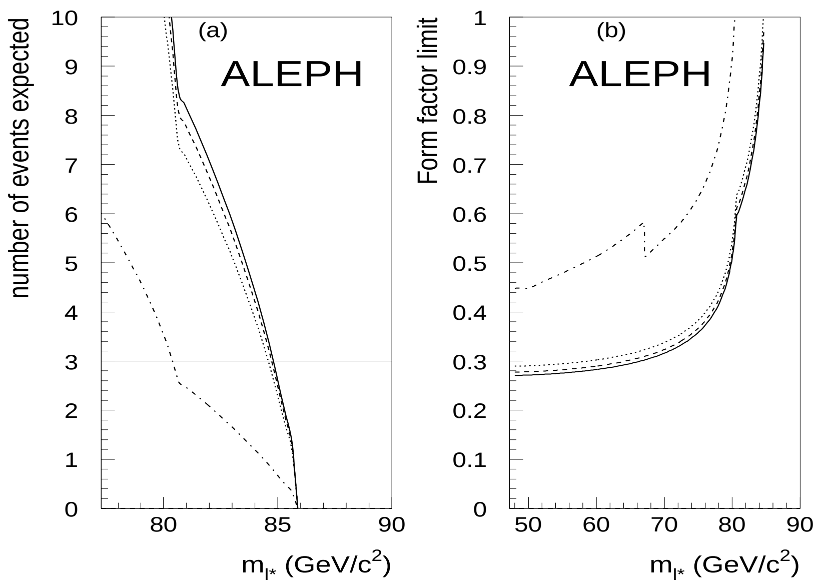

Figure 2: (a) Expected number of $\ell^*\bar{\ell}^*$ events as a function of ℓ^* mass; the excluded mass limits are shown by the horizontal line. (b) the excluded form-factor at 95% C.L. for $\ell^*\bar{\ell}^*$ production as a function of mass (mass limits are taken where the form-factor is unity). The dashed, solid, dotted and dot-dashed lines denote $\mathrm{e}^*\bar{\mathrm{e}}^*$, $\mu^*\bar{\mu}^*$, $\tau^*\bar{\tau}^*$ and $\nu^*\bar{\nu}^*$ respectively in both figures.

An event was a candidate in the electron channel if both tracks were identified as electrons and the p_t in the event was less than 30 GeV/c. Alternatively, the event was accepted into this channel if one track was identified as an electron, and the p_t was less than 10 GeV/c, provided that the other track was not identified as a muon.

An event was a candidate in the muon channel if both tracks were identified as muons and the p_t was less than 30 GeV/c. Alternatively, an event was accepted into this channel if one track was identified as a muon and the p_t was less than 10 GeV/c, provided that the other track was not identified as an electron.

An event was a candidate in the tau channel if the p_t was greater than 5 GeV/c and it was not accepted in either the electron or muon channels.

Tracks and photons were rescaled using energy and momentum conservation [9]. The invariant mass of the dilepton system (calculated with the rescaled momenta) was required to lie outside the range 84–97 GeV/c^2, removing a large fraction of the remaining background from the Zγ final state where the on-shell Z had decayed to a lepton pair.

Signal and background events were fully simulated. The electron background was studied using the BHWIDE [11] generator and the muon and tau backgrounds using the KORALZ generator. 68.5 events were predicted in the electron channel, 12.8 in the muon channel and 8.6 in the tau channel, while 60, 9 and 8 events respectively, were selected in data.

For the signal, the ESTAR [12] and MUSTAR [13] generators were used, with initial state radiation and with tau decays implemented [14]. The efficiencies for μ^* and τ^* were found to be around 60% and 50% respectively for most of the mass range. The lower efficiency for the τ^* case was due to the greater difficulty in reconstructing the events, as the τ directions were estimated from those of their decay products. The relevant e* efficiency arises from the combination of this channel with the eγ channel, which is dominant.

The invariant mass resolutions, σ, for μ^* and τ^* were $125\,\mathrm{MeV}/c^2$ and $2\,\mathrm{GeV}/c^2$ respectively. Limits for the μ^* and τ^* couplings are shown in Fig. 3, calculated using mass bins of width 4σ.

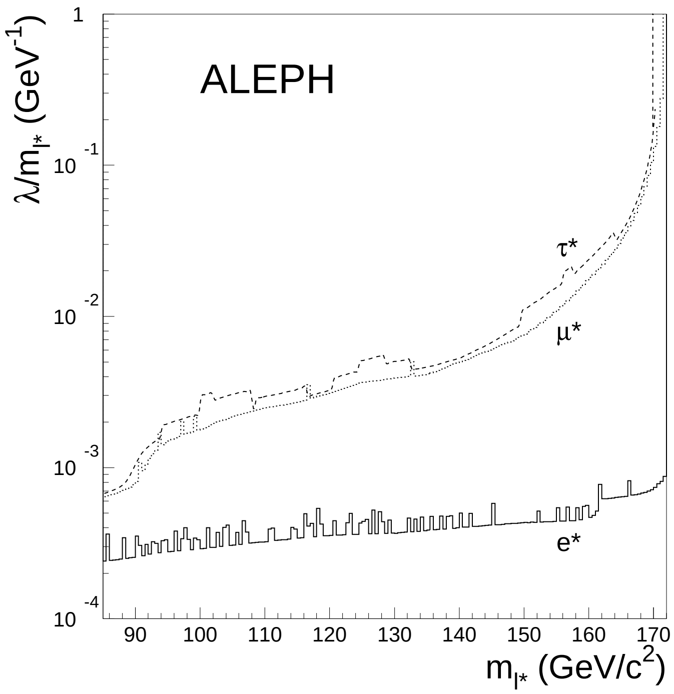

Figure 3: 95% C.L. exclusion limits from 161–172 GeV data in the mass-coupling plane for singly produced chiral ℓ^*.

2.2.1 Single production of excited electrons (eγ channel)

The main backgrounds come from:

- radiative Bhabha scattering with one of the final state electrons remaining undetected in the beam pipe;
- Bhabha scattering with one of the final state electrons transferring practically all of its energy to a photon through hard bremsstrahlung in the detector material, producing mostly back-to-back events;
- $\gamma\gamma$ final states with one of the photons converting in the detector material into an e^+e^- pair asymmetric enough for one of the electrons to escape detection.

The Monte Carlo generators TEEGG7 [15], BHWIDE and GGG [16] were used to study these backgrounds.

Events were selected containing exactly one track and one photon with both energies greater than 10 GeV. The beam axis was required to lie within the plane defined by the track and the photon to within $0.5°$, in accordance with the hypothesis that there was an undetected particle at very low angle. A track passing through the inner tracker typically produces 8 hits. Hence requiring the number of hits in the inner tracker to be less than a total of 12 for opening angles above 175°, removed background events resulting from hard external bremsstrahlung. Requiring the number of such hits to be at least four removed the background from asymmetric photon conversion.

In the e^* centre of mass frame, the decay photon emission direction favours that of the initial quasi-real photon [1], whereas the Compton process favours backscattered photons. This effect was exploited to enhance signal sensitivity by requiring the photon scattering angle in the laboratory frame to be greater than 30° and less than 135°.

Assuming a three particle final state and using only the polar angles of the detected particles, energy and momentum conservation [9] enable the energy, E_{miss}, to be calculated. In order to reject events with additional low angle photons, the total energy in the event as given by the detected particles plus E_{miss} was required to be more than 90% of the centre of mass energy.

The charged track had to be identified as an electron by the standard ALEPH identifiers, and the sign of its charge had to be the same as that of the beam particle whose direction was the same as the boost direction of the system defined by the detected particles. 48.5 events were expected while 46 e^* candidates were selected in the data, so there was no evidence of signal.

The signal was fully simulated using the ESTAR generator and the efficiency for the combined $ee\gamma$ and $e\gamma$ channels varied linearly from 40% for an e^* mass of $85\,\mathrm{GeV}/c^2$ up to 73% at the kinematic limit. The invariant mass resolution was $125\,\mathrm{MeV}/c^2$. The resulting exclusion limit is shown in Fig. 3.

3 Excited neutrinos

The search for pair-produced neutrinos employed only the radiative decay channel, but both radiative and weak decays (for ν_e^* only) were considered in the search for singly produced excited neutrinos. For cases where the event signature was one or two photons only, there was a considerable background from wrongly interpreted cosmic muon events and the analysis [17] was used to eliminate this kind of background. Photons are also identified if they convert producing an electron-positron pair. The principle background ($\nu\bar{\nu}\gamma(\gamma)$) was simulated with seven times more Monte Carlo luminosity than data.

3.1 Pair production

The radiative decay channel only was searched for. Two photons above 8 GeV were required in the event, the acoplanarity of the photons was required to be less than 177° (eliminating $e^+e^- \to \gamma\gamma$ QED events), and the missing mass was required to lie outside the range 82–$102\,\mathrm{GeV}/c^2$, removing events containing the neutrino-pair decay of an on-shell Z. One acoplanar photon pair event was found, against a background estimate of 1.7. The kinematically allowed mass range for the corresponding ν^* candidate was 31.1–$67.2\,\mathrm{GeV}/c^2$. The efficiency of the analysis for the fully simulated Monte Carlo signal was found to increase smoothly from 44%, for a ν^* of $45\,\mathrm{GeV}/c^2$ mass, to 76% at the kinematic limit. Hence there is no signal, and the mass limit for ν^* is 80.5 GeV/c^2. Limits on the form-factor associated with $\nu^*\bar{\nu}^*$ production are shown in Fig. 2.

3.2 Single production

The largest cross-section for excited neutrino production at these energies is for t-channel ν_e^* production, *via* W-exchange, in association with a standard ν_e. Other channels are not negligible, and are enhanced above their tree-level values by initial state radiation.

Two channels were searched for and the results combined. In the case where $f \neq f'$ the radiative decay of ν^* is allowed in addition to the weak decays. The case where $f = 1$ and $f' = 0$ was considered here. Exactly one photon, with an energy above 20 GeV was required. The missing mass of the event was required to exclude $\mathrm{Z} \to \nu\bar{\nu}$, in the mass range 82–102 GeV/c^2. Background events detected only by initial state radiation tagging favour low polar angles, so $|\cos\theta| < 0.8$ was imposed as a final cut. 18.2 events were expected, largely from $\nu\bar{\nu}\gamma(\gamma)$ background, and 16 were seen. Signal events were generated according to the model of Ref. [1]. Efficiencies for ν_e^* decrease from 57% for a mass of 85 GeV/c^2 to 50% at 125 GeV/c^2, then increase to 71% at the kinematic limit. For ν_μ^* and ν_τ^* efficiencies decrease from 53% to 45% and increase to 72% in the same pattern. There was no evidence of signal and limits on the ν^* couplings are shown in Fig. 4.

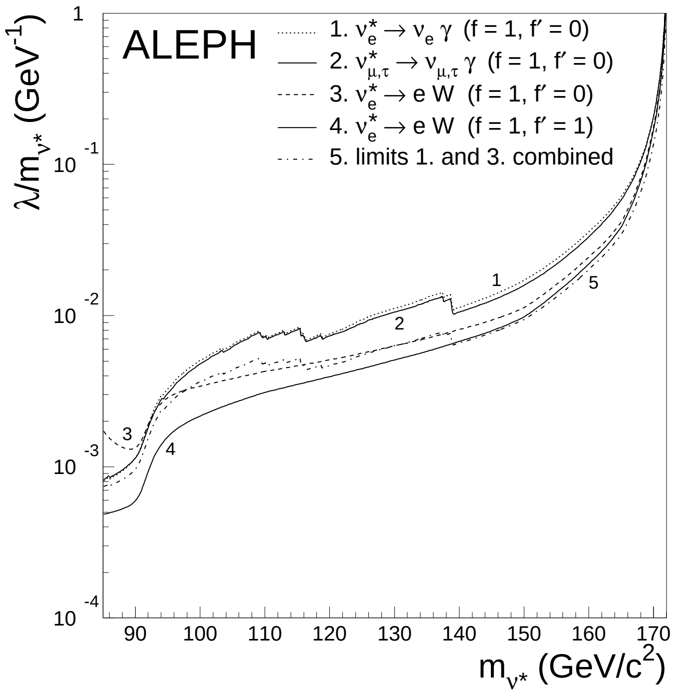

Figure 4: 95% C.L. exclusion limits from 161–172 GeV data in the mass-coupling plane for singly produced chiral ν^* as a function of ν^* mass.

In the case where $f = f'$, the $\gamma\nu^*\nu$ coupling vanishes and only weak decays are allowed. The signature of charged current decays is missing energy and an electron:

$$e^+e^- \to \nu_e \bar{\nu}_e^* \to \nu_e e W \to \nu_e e + \left\{ \begin{array}{c} q\overline{q}' \\ \ell\nu \end{array} \right. .$$

The case analysed was that of the weak charged current decay, with the resulting W decaying hadronically. The analysis was carried out as follows. Leptonic and most $\gamma\gamma$ events were removed by requiring more than eight charged tracks. The total energy seen in the calorimeter within $12°$ of the beam axis was required to be $< 0.5\,\mathrm{GeV}$ to reduce events incompletely contained in the detector acceptance. The visible energy in the event had to be larger than 90 GeV, which removed all remaining $\gamma\gamma$ events. At energies above the Z peak many events contain a hard radiative isolated photon. To remove such background events it was required that the energy in a cone of $10°$ opening angle around the most energetic photon be greater than 1 GeV. In signal events the W recoils from a neutrino of high momentum, usually within the detector acceptance. Accordingly it was required that the energy in a cone of $10°$ opening angle around the missing momentum vector be less than 1 GeV, that the polar angle of the missing momentum vector be greater than $18.2°$ and that the total missing momentum be greater than $5\,\mathrm{GeV}/c$. At least one track had to be identified as an electron, with energy ($> 8\,\mathrm{GeV}$) and hence unlikely to arise from a jet. The mass of the system formed by all the other particles in the event (by hypothesis the hadronically decaying W) was required to be between 69 and $91\,\mathrm{GeV}/c^2$. For events containing more than one electron, the condition had to be fulfilled for at least one of them. WW background was eliminated by requiring that the invariant mass of the electron-neutrino system (with the neutrino momentum identified by hypothesis with the missing momentum vector) be unlike a decaying W, i.e. not in the range 68–$85\,\mathrm{GeV}/c^2$ for the 161 GeV data and not in the range 68–$91\,\mathrm{GeV}/c^2$ for the 172 GeV dataset.

The background processes considered were $q\overline{q}$, Weν and Zee, generated using PYTHIA [18], $\gamma\gamma$ events generated using PHOT02 [19] and WW events generated using LPWW02 [20]. After all the cuts, 2.1 events were expected and none was observed, so there was no evidence of signal.

The signal generator was based on [21], a heavy neutral lepton generator that produces identical topologies to the model of ν_e^* in [1], which was used for cross-section calculations. All events were fully simulated in the ALEPH detector Monte Carlo. The overall signal efficiency, including branching ratios, for ν_e^* masses in the range 85–$150\,\mathrm{GeV}/c^2$ was approximately 37%, with small fluctuations dependent on ν^* mass, which have been taken into account in determining the limit. Fig. 4 shows the 95% C.L. limits for the coupling $\lambda/m_{\nu_e^*}$ from radiative decay and weak decay and the combined limit. The omission of searches for neutral current decays has been taken into account.

4 Conclusion

Excited leptons were searched for in the data collected by ALEPH at $161-172\,\mathrm{GeV}$. No evidence for a signal was found. Excited states were excluded at 95% confidence level for masses up to $84.7\,\mathrm{GeV}/c^2$ for e^*, $84.8\,\mathrm{GeV}/c^2$ for μ^*, $84.5\,\mathrm{GeV}/c^2$ for τ^* and $80.5\,\mathrm{GeV}/c^2$ for ν^*. For single production, the 95% C.L. exclusion limits on the couplings, λ/m_{ℓ^*}, for an excited lepton mass of $150\,\mathrm{GeV}/c^2$ are $0.0004\,\mathrm{GeV}^{-1}$ for e^*, $0.007\,\mathrm{GeV}^{-1}$ for μ^*, $0.01\,\mathrm{GeV}^{-1}$ for τ^* and $0.015\,\mathrm{GeV}^{-1}$ for ν^*.

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