Searches for sequential and excited heavy leptons at LEP.

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Abstract. This paper summarizes searches for sequential and excited heavy leptons at LEP2 using 1996 data (center of mass energies 161 and 172 GeV).

I Introduction.

In spite of great success of Standard Model it is widely believed not to be the final theory. Many extentions of the Standard Model predict new leptons [1]. These leptons are assumed to be either sequential (having the same quantum numbers as the ordinary leptons), or exotic, that have no analog in Standard Model (mirror fermions, vector fermions, isosinglet neutrinos). The leptons are usually assumed to be elementary. But some models suggest that even the ordinary leptons are composite. This leads to existance of their excited states.

A search for new particles becomes a major objective whenever a new energy frontier is achieved. Searches for new leptons at LEP1 led to the exclusion of masses of new leptons below about half of the Z mass. This implies that a fourth generation neutrino (if it ever exists) is heavy. LEP2 operation in 1995 at 130 and 136 GeV has pushed further mass limits [2].

In 1996 LEP2 achieved new energies: 161 and 172 GeV at center of mass. Integrated luminosity collected per experiment was about $10pb^{-1}$ at each energy. Searches were performed by LEP collaborations for stable and unstable heavy leptons and for excited heavy leptons.

II Unstable heavy sequential leptons.

Sequential heavy leptons may only be produced in pairs through γ/Z exchange in s-channel:

$$e^+e^- \to L^+L^-, L^0\overline{\mathrm{L}}^0$$

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It is assumed that they have the same couplings to γ and Z as usual leptons. The heavy neutrino L^0 may be of Dirac or Majorana type. The cross section for Majorana type neutrinos falls more rapidly with mass than the cross section for Dirac type neutrinos. A heavy lepton can decay through the charged current channels ($L^\pm \to \nu_\ell W^{\pm *}$; $L^0 \to \ell^\pm W^{\mp *}$; $L^\pm \to L^0 W^{\pm *}$) or the neutral current channels ($L^\pm \to \ell^\pm Z^*$; $L^0 \to \nu_\ell Z^*$), where $\ell^\pm = e, \mu, \tau$. Since the charged current decay channels are dominant, they were engaged in searches. In decay channel $L^\pm \to L^0 W^{\pm *}$ heavy neutrino L^0 was assumed to be longlived and escape detection. To avoid lepton flavor changing neutral currents at the one-loop level a mixing with only one generation of usual leptons was assumed.

The searches (at 161 and 172 Gev) were performed by L3 [3] and OPAL [4] collaborations. OPAL results at 172 GeV are preliminary.

As an example let's consider OPAL selection at 172 GeV for the cascade process

$$\begin{array}{c} e^+e^- \to L^+L^- \\ L^- \to \nu_\ell W^{-*} \; ; \; W^{-*} \to q_i\bar{q}_j, \; \ell^-\bar{\nu}_\ell \\ L^+ \to \bar{\nu}_\ell W^{+*} \; ; \; W^{+*} \to q_k\bar{q}_\ell, \; \ell^+\nu_\ell \end{array} \tag{1}$$

This process produces mainly multijet events with large transverse momentum or transverse missing energy. A set of cuts was applied. First, multihadronic events were selected (at least 5 good tracks, 7 good clusters, raw energy in good clusters more than 10% of the center of mass energy, longitudinal energy (sum of clusters energies multiplied by cosines of their polar angles) less than 65% of visible raw energy). Then to suppress $q\bar{q}\gamma$ and two gamma events, energy in different forward calorimeters was required to be less than 2 or 5 GeV. Non-radiative events were selected by applying a cut $|cos\theta_{miss}| < 0.85$. To reject events containing back-to-back jets the trust of the event was required to be less than 0.85. Further two different sets of cuts were applied for events containing and not containing isolated leptons (see (1)). The cuts isolate phase-space regions populated by expected signal events. For events without leptons: $80 < E_{vis} < 145$ GeV, $p_{Tmiss} > 15$ GeV, $N_{jets} \geq 4$, the maximum momentum of a good track ≤ 25 GeV. For events with one or more isolated leptons: $40 < E_{vis} < 100$ GeV, $p_{Tmiss} > 20$ GeV, $N_{jets} \geq 3$.

After all cuts only 1 event was found in the data while 3 events were expected from background. The selection efficiency was $(25.9 \pm 1.0)\%$ for $m_L = 75$ GeV and $(21.8 \pm 0.9)\%$ for $m_L = 80$ GeV. 3.2 signal events were expected for $m_L = 80$ GeV. The 95% C.L. lower limit derived for heavy lepton mass is 80.2 GeV.

Similarly dedicated selections for each channel leaved no or very few candidate events in good agreement with expected background. The calculated 95% C.L. upper limit for number of signal events was compared with a mass dependence of expected number of signal events. Resulting lower mass limits are listed in the table 1 (combined for 161 and 172 GeV).

TABLE 1. Lower 95% C.L. mass limits for unstable heavy sequential leptons.

	Charged heavy lepton $L^\pm$		Neutral heavy lepton L^0 Dirac type			Majorana type		
Decay	$\nu_\ell W^\pm$	$L^0 W^\pm$	$e^\pm W^\mp$	$\mu^\pm W^\mp$	$\tau^\pm W^\mp$	$e^\pm W^\mp$	$\mu^\pm W^\mp$	$\tau^\pm W^\mp$
L3	78.7	81.0	78.0	78.0	72.2	66.7	66.7	58.2
OPAL	80.2	81.4	79.1	78.5	69.0	69.8	68.7	55.7

III Stable new leptons.

If $m_{L^0} > m_{L^\pm}$ and a charged heavy lepton doesn't mix with light neutrinos $L^\pm$ will appear to be stable. A search for pair-produced, long-lived, singly-charged, not strongly interacting heavy particles was performed by ALEPH [5] and L3 [3] collaborations. Production of charged stable heavy leptons would be seen in the detectors as a pair of back to back tracks and the tracks would be highly ionizing. The search is based on the energy loss (dE/dx) information from a central tracking chamber.

In L3 search [3] the events were selected with two back to back tracks (in polar angle range $|\cos\theta| < 0.82$) having acollinearity less than 15^o and momentum of each track greater than 5 GeV. The track energy loss dE/dx was normalized to 1.0 for a $\beta \approx 1$ particle. Both tracks were required to have an energy loss between 1.25 and 8 units. No such events were found in the data. The selection efficiency at $\sqrt{s} = 172$ GeV passing all cuts varied from 64% at $m_L = 70$ GeV to 68% at $m_L = 83$ GeV. Outside this mass region the efficiency for both tracks to satisfy the selection criteria falls down to zero. For $m_L < 68$ GeV heavy lepton would have enough energy to penetrate the calorimeters and to appear in the muon chambers. This would create considerable excess in dimuon events (13 additional events at $m_L = 68$ GeV to 34 expected from Standard Model for $\sqrt{s} = 172$ GeV). Only 32 dimuon events were observed in data, which excludes at 95% C.L. heavy leptons with mass less than 68.2 GeV. Comparing the number of expected heavy lepton events for different heavy lepton masses (at $\sqrt{s} = 133 - 172$ GeV) with 95% C.L. upper limit on the number of signal events a lower limit on stable heavy lepton mass was found to be 84.2 GeV. Absence of signal corresponds to a cross section upper limit (for mass 60-84 GeV, charge ± 1e and for luminosity weighted average energy) of between 0.3-0.5 pb at 95% C.L.

Similarly ALEPH [5] searched for exactly two back to back tracks away from beam axis ($|\cos\theta| < 0.90$) with acollinearity less than 20^o which must be well reconstructed in a central tracking chamber (TPC) and have equal momenta within three measurement errors. For each particle a mass was calculated as $m_i = \sqrt{E_{beam}^2 - p_i^2}$. In different mass regions different selections were applied. In the so called low-mass selection (both particles have masses $0.52 < m_{1,2}/E_{beam} < 0.80$) acollinearity must be less than 6^o and dE/dx information was not used since particles produce ionization similar to minimum

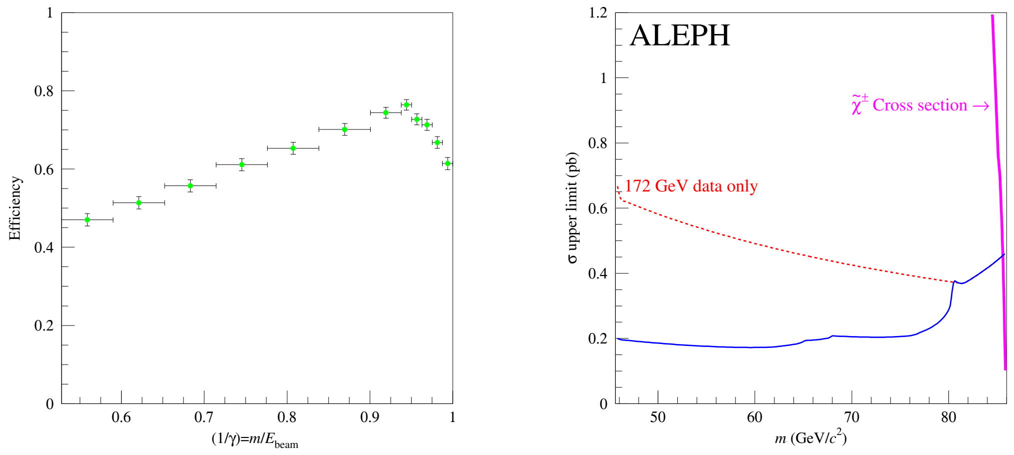

FIGURE 1. (a) Selection efficiency for spin 1/2 stable charged particles as a function of m/E_{beam} (ALEPH). (b) 95% C.L. upper limit on the production cross section for spin 1/2 particles as a function of mass at $\sqrt{s} = 172$ GeV.

ionizing particle. In intermediate-mass region ($0.80 < m_{1,2}/E_{beam} < 0.98$) sum for the two tracks of deviations from muon ionization should be more than 10 measurement errors. For masses close to the kinematic limit ($m/E_{beam} \simeq 1$) a selection takes into account that high ionization saturates TPC electronics, but tracks can be detected in inner tracking chamber (ITC), which do not allow alone a kinematic reconstruction. Then heavy particles are expected to produce small energy depositions in calorimeters (less than 5 GeV) with roughly back-to-back topology. No events (at $\sqrt{s} = 133 - 172$ GeV) survived any of these three selections. Dependence of selection efficiency from m/E_{beam} for spin 1/2 stable charged particles is shown on Figure 1(a). Derived 95% C.L. upper limit on the production cross section for these particles at $\sqrt{s} = 172$ GeV is shown on Figure 1(b). The dashed curve is obtained using $\sqrt{s} = 172$ GeV data only. The solid curve - for all high energy data when integrated luminosity was rescaled to $\sqrt{s} = 172$ GeV using dependence of cross section on $\sqrt{s}$. Very similar limits were derived for spin 0 particles [5].

More general search for heavy stable (or long-lived) particles was performed by DELPHI collaboration [6]. Particles were assumed not to interact more strongly than ordinary hadrons and to have a charge $\pm e$ or $\pm 2/3e$. Tracks of these particles were searched in all events with a total momentum in each hemisphere more than 10 GeV, and tracks with momentum at least 5 GeV were considered. Tracks were required to have a momentum measured with better than 100% error and to have a length more than 30 cm. The search was based on the ionization loss measurement in TPC and particle identification in the Barrel Ring Imaging Cherenkov detector (RICH), with acceptance $|\cos\theta| < 0.68$. Both gas and liquid RICH counters were used in the veto mode: zero photons in gas radiator (for momenta above 5 GeV) and not more than 4 photons (for momenta above 15 GeV) in liquid radiator (four and not zero due to backgrounds). Also the condition for liquid radiator was used only in bottom half of detector to avoid a background from cosmic muons. Two dE/dx selections were applied: 1)the measured normalized ionization loss was anomalously high - above 2 and below 10; 2)the ionization loss was anomalously low - below the proton expectation by at least 0.3 units (this was designed for charge $\pm 2/3e$ particles).

After applying the selections no candidate particles were found (for all energies $\sqrt{s} = 133 - 172$ GeV). Efficiencies as a function of the mass were obtained with simulation studies of pair production of heavy stable particles. Upper 95% C.L. limit on the production cross section (for highest masses $m_L = 70 - 84$ GeV) is about 0.4 pb at 161 and 172 GeV [6].

IV Excited leptons.

The existence of excited leptons would confirm composite models [7], which could give a natural explanation of such fundamental quantities as the number of families and the fermion masses .

Excited leptons can be produced in pairs ($e^+e^- \to \ell^*\ell^*$) or singly together with an ordinary lepton ($e^+e^- \to \ell\ell^*$). The $\ell^*\ell^*V$ couplings (where ℓ^* is e^*, μ^*, τ^* or ν^* and V is Z or γ) are assumed to be the same as for ordinary leptons.

The single production of excited leptons and their decays are governed by $\ell\ell^*V$ couplings. The effective electroweak Lagrangian has the form:

$$L_{\ell\ell^*} = \frac{1}{2\Lambda}\overline{\ell}^*\sigma^{\mu\nu}\left[gf\frac{\tau}{2}W_{\mu\nu} + g^{'}f^{'}\frac{Y}{2}B_{\mu}\right]\ell + \text{hermitian conjugate},$$

where Λ is the compositeness mass scale, f and $f^{'}$ describe the effective changes from SM coupling constants g and $g^{'}$. If $|f| = |f^{'}|$ (or one of f equal to zero), then $f/\Lambda(= \sqrt{2}\lambda/m_{\ell^*})$ remains the only free parameter in the Lagrangian.

An excited lepton decays immediatelly radiating γ, Z or W. Table 2 gives an idea about branching ratious. For the assignment $f = -f^{'}$ the $\ell^{*\pm} \to \ell^{\pm}\gamma$ decays are forbidden; for the complimentary assignment $f = f^{'}$ the $\nu^* \to \nu\gamma$ decays are forbidden.

Decays of excited leptons into its ground states with emission of a photon (photonic decays) and decays to W (charged decays), more significant than decays to Z, were used in searches. Results of searches at 161 GeV were published in [8]. All collaborations have preliminary results at 172 GeV (OPAL perliminary results are given in [9]).

Photonic decays of excited leptons have the most clear signatures. In OPAL search for photonic decays of pair produced charged excited leptons events were selected with two identified leptons of the same flavour and two photons.

TABLE 2. Branching ratious in % for decays of excited leptons.

Decay channel	$m = 80$ GeV $f = f'$	$f = -f'$	$m = 160$ GeV $f = f'$	$f = -f'$
$\ell^{*\pm} \to \ell^{\pm}\gamma$	100.0	0.0	38.6	0.0
$\ell^{*\pm} \to \ell^{\pm}Z^{o}$	0.0	0.0	8.4	35.3
$\ell^{*\pm} \to \nu W^{\pm}$	0.0	100.0	53.0	64.7
$\nu^{*} \to \nu\gamma$	0.0	100.0	0.0	38.6
$\nu^{*} \to \nu Z^{o}$	0.0	0.0	35.3	8.4
$\nu^{*} \to \ell^{\pm}W^{\mp}$	100.0	0.0	64.7	53.0

Then the sum of energies of two leptons and two photons (E_{tot}) was required to be $1.6 \cdot E_{beam} < E_{tot} < 2.4 \cdot E_{beam}$. Difference between $\ell\gamma$ masses (in one of two combinations) must be less than 10 GeV. No events were found in data. Efficiency of the selection (for $m_{\ell^*} = 85$ GeV) is equal $(56.0 \pm 1.1)\%$ for e^*e^*, $(57.6\pm1.1)\%$ for $\mu^*\mu^*$ and $(35.0\pm1.0)\%$ for $\tau^*\tau^*$. In searches for charged decays of pair produced excited leptons topologies are almost identical to neutral and charged unstable heavy leptons, and analysis is very similar (see section II). The results of searches for pair produced excited leptons (95% C.L. lower mass limits) are reported in table 3.

TABLE 3. Lower 95% C.L. mass limits for pair produced excited leptons.

Decay	Photonic $f = f'$			Charged $f = -f'$	Photonic $f = -f'(f \neq f')$	Charged $f = f'$		
	e^*	μ^*	τ^*	ℓ^*	ν^*	$\nu_e{}^*$	$\nu_\mu{}^*$	$\nu_\tau{}^*$
ALEPH	84.7	84.7	84.5					
DELPHI	84.6	84.6	84.6	74.6	80.1	67.6	67.6	67.6
L3	85.1	85.0	84.1		78.9			
OPAL	85.1	85.1	84.1	80.6	85.1	84.0	83.9	79.5

In searches for single production of excited leptons all found events were in good agreement with Standard Model processes. Upper limits were derived (combining all high energy data) on coupling constants λ/m_{ℓ^*} as functions of m_{ℓ^*} up to the kinematic limit (see Figure 2).

V Conclusion.

No new leptons were found below masses $\sim 80 - 85$ GeV. The next step is a search for new leptons in 1997 184 GeV data.

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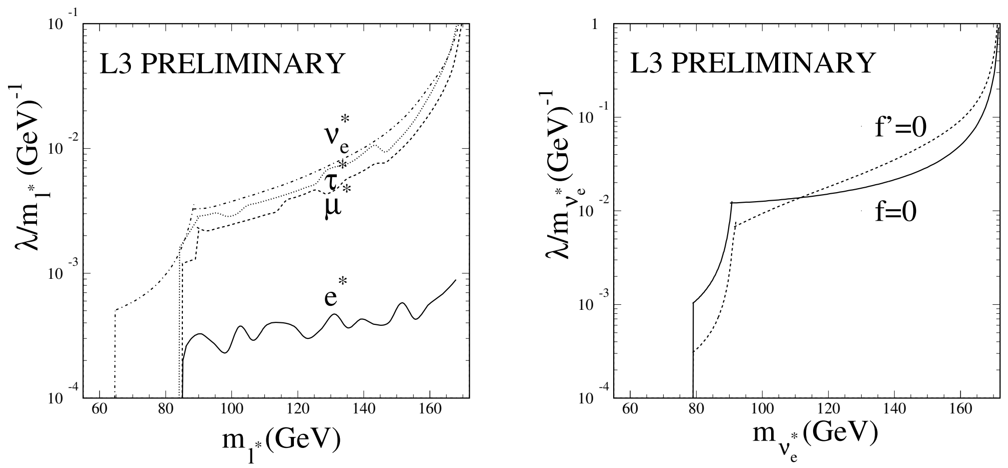

FIGURE 2. (a) The upper limit on the coupling constant λ/m_{ℓ^*} at 95% C.L. for excited leptons with $f = f^{'}$. (b) The upper limit on the coupling constant $\lambda/m_{\nu_e^*}$ at 95% C.L. for $f = 0$ and $f^{'} = 0$.

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