A SEARCH FOR NEW QUARKS AND LEPTONS FROM Z ° DECAY AT LEP ALEPH Collaboration

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ALEPH Collaboration

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A search for Z^0 decays into pairs of possible new heavy quarks (t and b′), new heavy charged leptons ($L^\pm$), stable heavy neutral leptons (ν_L) and unstable heavy neutral leptons (L^0) is performed on data collected by the ALEPH detector corresponding to 11 550 events of $Z^0 \to$ hadrons. The limits on the masses of the heavy quarks are $M_t > 45.8$ GeV and $M_{b'} > 46.0$ GeV, allowing for both charged-current and flavor-changing neutral-current decays of the b′. If an $L^\pm$ decays into a stable ν_L, then for $M_{\nu_L} < 42.7$ GeV, the mass of $L^\pm$ is excluded for all values of $M_{L^\pm} > M_{\nu_L}$. Finally, while the mass of the stable ν_L is excluded up to 42.7 GeV, the mass of the unstable L^0 is excluded up to 45.7 GeV with the mixing parameters $|U_{\ell L^0}|^2$ down to 10^{-13} at this mass. For 25.0 GeV $< M_{L^0} < 42.7$ GeV, all values of $|U_{\ell L^0}|^2$ are excluded. All limits are given at 95% CL.

1. Introduction

The recent operation of the Large Electron–Positron Collider, LEP, at CERN, provides an excellent opportunity to carry out searches for new particles. Using data recorded during the first period of LEP operation from September 19 to November 7, 1989, we have performed searches for a top quark (t), a fourth-generation charge $-\frac{1}{3}$ bottom type quark (b′), a sequential heavy charged lepton ($L^\pm$), an unstable neutral heavy lepton (L^0) and a stable neutral heavy lepton (ν_L) from Z^0 decay. In all these cases, a Z^0 is assumed to decay into a pair of these new quarks or new leptons with a decay rate given by the standard model. The processes studied are:

$$Z^0 \to t\bar{t}\,, \tag{1}$$

$$Z^0 \to b'\bar{b}'\,, \tag{2}$$

$$Z^0 \to L^+L^-\,, \tag{3}$$

$$Z^0 \to L^0\bar{L}^0\,, \tag{4}$$

$$Z^0 \to \nu_L\bar{\nu}_L\,. \tag{5}$$

The decays of t, b′, $L^\pm$, L^0 are via a charged-current process into a virtual W boson (W^*):

$$t \to bW^*\,,$$

$$b' \to cW^*\,,$$

$$L^\pm \to \nu_L W^* \quad (\nu_L \text{ stable})\,,$$

$$L^0 \to \ell W^* \quad (\ell = e, \mu, \tau)\,.$$

In addition, the decays of b′ via flavor-changing neutral-current are also considered:

$$b' \to b\gamma$$

and

$$b' \to bg\,.$$

Recently, the ALEPH Collaboration has determined, on the basis of the cross section for $e^+e^- \to$ hadrons at the Z^0 peak, the number of light neutrino species to be 3.01 ± 0.16 [1,2] [#1]. This result implies that there is no fourth-generation light neutrino. Because of the high accuracy of this result,

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[#1] In ref. [2], about 18 500 hadronic events are used for the analysis.

one can set a limit on the mass of a stable heavy fourth-generation neutrino (or neutral lepton). On the other hand, if the fourth-generation neutral lepton is unstable, then this result [1,2] gives a rather poor limit on the mass. For this reason, it is desirable to carry out a direct search for unstable neutral leptons (L^0). We consider the case where there is mixing between the neutral heavy lepton and the three light neutrinos. If the mixing parameters of L^0 with ν_e, ν_μ and ν_τ are U_{eL^0}, $U_{\mu L^0}$ and $U_{\tau L^0}$ respectively, then L^0, which is the decay product of the Z^0 as indicated by (4), contains the terms

$$U_{eL^0}|\nu_e\rangle + U_{\mu L^0}|\nu_\mu\rangle + U_{\tau L^0}|\nu_\tau\rangle .$$

With such mixing, the heavy neutral lepton L^0 can decay into a virtual W together with an e, a μ or a τ.

The study of processes (1)–(5) is performed using data collected with the ALEPH detector with an integrated luminosity of 542 nb^{-1} at center-of-mass energies from 88.3 GeV to 94.3 GeV. This corresponds to 11 550 $Z^0 \to$ hadrons events. This paper describes the search for processes (1)–(5), with the following topologies or methods:

(i) Search for charged-current decays of t, b′ and L^0 by the topology of an isolated charged particle. The isolated charged particle is the $e^\pm$, $\mu^\pm$ or one-prong decays of the $\tau^\pm$, resulting from the leptonic or semi-leptonic decay of the new quark or new lepton.

(ii) Search for the flavor-changing neutral-current decay of b′ by a topology of an isolated photon ($b' \to b\gamma$) or of a four-jet final state ($b' \to bg$, $\bar{b}' \to \bar{b}g$).

(iii) In the case of $Z^0 \to L^0\bar{L}^0$, when the lifetime of L^0 is long, as explained below, the topology of the events could be one or two displaced vertices.

(iv) Using the total hadronic cross section measurement at the Z^0 peak, mass limits can be set for ν_L and $L^\pm$ on the processes $Z^0 \to \nu_L\bar{\nu}_L$ and $Z^0 \to L^+L^-$, where $L^\pm \to \nu_L W^*$. For the long-lived L^0, limits can be set on $|U_{\ell L^0}|^2$ as a function of M_{L^0}.

2. The ALEPH detector

The ALEPH detector is described in detail elsewhere [3]. The parts of the detector relevant to this analysis are the inner tracking chamber (ITC), the large time projection chamber (TPC), the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). A 1.5 T magnetic field is provided by the superconducting solenoid surrounding the TPC and ECAL. The luminosity calorimeter (LCAL) provides energy and position measurements of the showers produced by the small-angle Bhabha scattering $e^+e^- \to e^+e^-$. The readout of the apparatus is triggered independently by several separate conditions, one of which is most relevant to this study. The total energy trigger demands a deposition of energy in the ECAL such that the energy in the barrel is greater than 6.6 GeV or the energy in either endcap is greater than 3.7 GeV, or 1.5 GeV each in both endcaps.

3. Search for charged-current decay of t, b′ and L^0 by a topology of an isolated charged particle

A search for new quarks (t, b′) and new neutral heavy leptons (L^0) is performed by identifying a topology where there is an isolated charged particle in an event from the leptonic or semi-leptonic decay of the t, b′ or L^0. In this analysis, as well as the analysis described in section 4, both charged and neutral particles are used. A charged particle is required to have at least 4 TPC coordinates, $|d_0| < 2$ cm and $|z_0| < 5$ cm (for L^0, $|d_0| < 7$ cm and $|z_0| < 10$ cm), where d_0 is the distance of closest approach to the interaction point in the plane perpendicular to the beam axis and z_0 is the coordinate along the beam with respect to the interaction point. At least five charged particles are required in an event. The total charged energy in the event is required to be greater than 9 GeV. A neutral particle is defined as an electromagnetic cluster in the ECAL which is not associated with a charged particle. The energy of an ECAL neutral cluster is required to be greater than 0.5 GeV.

Selection criteria for the events are: (i) the vector sum of the transverse momenta $|\Sigma \boldsymbol{P}_T|$ of all particles with respect to the beam axis must be greater than 8 GeV/c; (ii) the aplanarity (A) of the event is greater than 0.03.

Selection criteria for an isolated charged particle are: (i) the charged particle is required to have $P_T > 3$ GeV/c where P_T is defined as the transverse momentum of the charged particle with respect to the thrust axis of the event; (ii) for each charged particle i, the isolation parameter ρ_i is calculated by performing a jet analysis using the LUND cluster algorithm [4] [#2] on all the charged particles of the event, except particle i. Here ρ_i is defined as [5]

$$\rho_i = \min_{\text{jet}\, j} \sqrt{2E_i(1-\cos\theta_{ij})} ,$$

where E_i is the energy in GeV of the ith charged particle and θ_{ij} is the angle between the ith particle and the axis of the jth jet. Events are accepted if $\rho > 1.8$, where ρ = maximum of (ρ_i). Fig. 1 shows the distributions of the isolation parameter ρ for the data and for the simulated events, normalized to the same integrated luminosity as the data, of b′ at 40 GeV mass after applying all other selection criteria. The cut is at 1.8.

Using the event and isolated charged particle selection criteria, 6 events are observed in the data and 6.5 events are expected from the Monte Carlo simulation of the background from $Z^0 \to q\bar{q}(g)$. Hence we can exclude at 95% CL mass ranges of t, b′ and L^0 for which we would have observed more than 6.2 events.

First-order QCD corrections [6] are included to calculate the cross section and hence the expected

[#2] In the algorithm, the jet-forming cutoff parameter d_{join} is changed from its default value to $d_{\text{join}} = 2.0$ GeV.

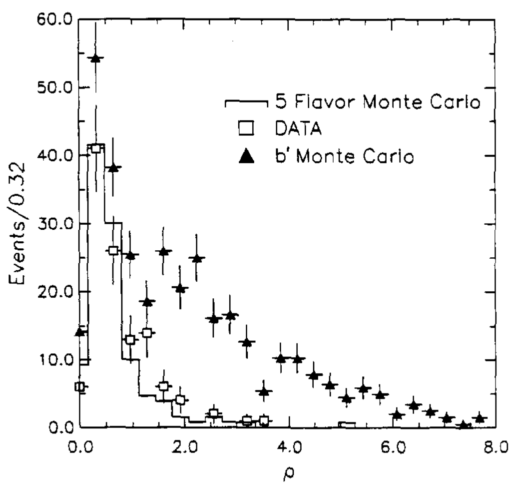

Fig. 1. Distributions of the isolation parameter ρ, after applying all other selection criteria, for the data and the Monte Carlo simulated events, normalized to the same integrated luminosity as the data, for $Z^0 \to b'\bar{b}'$ at 40 GeV mass. The cut is at $\rho = 1.8$.

number of events for t and b′. The simulated events for $Z^0 \to t\bar{t}$, $b'\bar{b}'$ and $L^0\overline{L^0}$ are processed by the same reconstruction and analysis programs as those used for the real data. To implement the jet fragmentation, the LUND parton shower model version 6.3 [7] is used, which is known to describe the data well [8–10]. Trigger efficiencies are calculated using a Monte Carlo simulation program which models the trigger conditions of the ALEPH detector and has been tuned to and tested with the data from the processes $Z^0 \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ and hadrons. In most of the cases under study, the trigger efficiencies are similar to those of $Z^0 \to$ hadrons, namely 100% [1,2]. The detection efficiencies after all event selection criteria depend on the quark and lepton masses and are about 14% for t and b′, 28% for $L^0 \to eW^*$ or μW^* and 22% for $L^0 \to \tau W^*$ at a mass of 40 GeV.

The systematic errors on the expected number of detected events are estimated as follows. An uncertainty of 1.3% comes from the integrated luminosity. The uncertainty in the cross section varies between 3% at 25 GeV and 22% at 45 GeV for both t and b′, due to an uncertainty of 25% in the higher order QCD correction [6]. The uncertainty due to the quark fragmentation parameter and the semileptonic branching ratio is about 5% for t, b′ and 2% for L^0. The uncertainty due to Monte Carlo statistics and detector simulation is about 4%. All errors are added in quadrature.

Figs. 2a–2c give the expected number of events after applying the event selection criteria for t, b′ and L^0 as a function of mass with the 95% CL limits indicated. The corrections due to different production cross sections at the different center-of-mass energies in the data are taken into account. In all cases we set the limit using the number of events expected minus 1.64 (one-sided 95% CL limit) times the total systematic error. For the charged-current decays of t, b′, and L^0, the following regions of mass are excluded at 95% CL:

$$26.0\ \text{GeV} < M_t < 45.8\ \text{GeV} ,$$

$$26.0\ \text{GeV} < M_{b'} < 46.2\ \text{GeV} ,$$

$$25.0\ \text{GeV} < M_{L^0} < 45.7\ \text{GeV} .$$

These results extend the earlier ones from TRISTAN [11]. Those on the quarks t and b′ overlap with the results from proton–antiproton colliders [12–14],

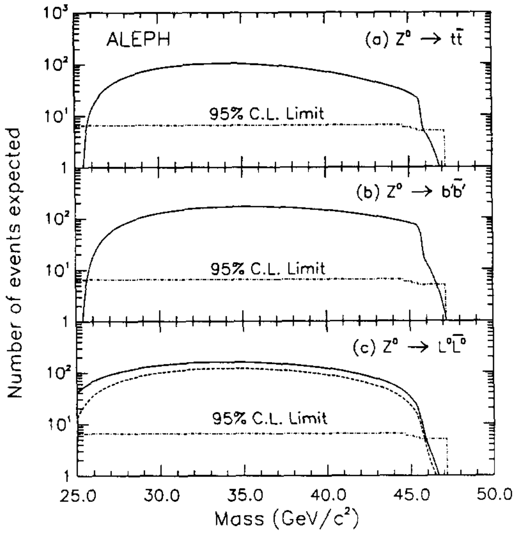

Fig. 2. (a) The number of expected events for $Z^0 \to t\bar{t}$ after applying the event selection criteria as a function of t mass. The 95% CL limit is indicated. (b) The same as (a) but for $Z^0 \to b'\bar{b}'$. (c) The same as (a) but for $Z^0 \to L^0\bar{L}^0$. The solid curve is for $L^0 \to eW^*$ or μW^* and the dashed curve for $L^0 \to \tau W^*$.

and are similar to the recent ones from MARK II [15] and OPAL [16]. The result on the neutral heavy lepton extends the limit given by MARK II [15].

4. Search for flavor-changing neutral-current decay of b′ by a topology of an isolated photon or of a four-jet final state

If a b′ exists with mass less than half of the Z^0 mass and with the present limit of t mass being larger than half of the Z^0 mass, the rate of the charged-current decay is via $b' \to cW^*$, which is expected to be suppressed by the small coupling $V_{cb'}$ [17]. The result, shown in fig. 2b, rules out the existence of a b′ for mass below 45.0 GeV if the rate of the charged-current decay is larger than 10%. It has been pointed out that flavor-changing neutral-current b′ decays could occur with a sizeable rate [17,18]; such decays are expected to be dominated by $b' \to b\gamma$ and $b' \to bg$. A search for such processes is described below. The selection of charged and neutral particles, and the simulation of the $Z^0 \to b'\bar{b}'$ process [#3] as well as the background process of $Z^0 \to q\bar{q}(g)$ follow the description given in section 3.

(i) $b' \to b\gamma$. The following description of the analysis applies to both cases: (1) $Z^0 \to b'\bar{b}'$ where both b′ decay to bγ, and (2) $Z^0 \to b'\bar{b}'$ where one b′ decays to bγ and the other to bg. In both cases, we search for a high-energy isolated photon in an event. Using the same definition of variables as given in section 3, the event selection criteria are: thrust $(T) < 0.8$, aplanarity $(A) > 0.03$, photon energy and transverse momentum with respect to the thrust axis greater than 10 GeV and 3 GeV/c, respectively. Finally, the isolation parameter ρ for the photon is required to be greater than 2.5. The detection efficiency for $b' \to b\gamma$ is 30% at 40 GeV mass. With these event selection criteria, 4 events are observed in the data while a background of 2.0 is expected from the background simulation of $Z^0 \to q\bar{q}(g)$ based on five quarks. Since a 95% CL limit corresponds to 7.2 expected events, we can exclude the branching ratio of $b' \to b\gamma$ greater than 5% for a b′ mass between 26.0 GeV and 46.0 GeV at 95% CL as shown in fig. 3n (left-hand side coordinate).

(ii) $b' \to bg$. A $Z^0 \to b'\bar{b}'$ event with both b′ decaying into bg gives a four-jet final state. Particles in each event with thrust $(T) < 0.8$ and aplanarity $(A) > 0.2$ are required to group into four jets using the LUND

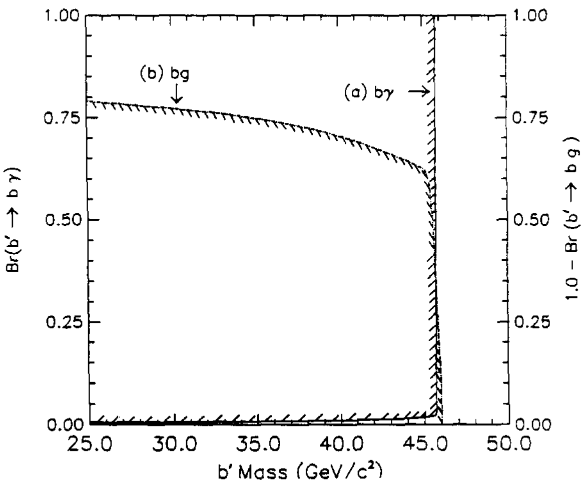

Fig. 3. The excluded region in decay branching ratios at 95% CL limit for (a) $b' \to b\gamma$ and (b) $b' \to bg$ as a function of b′ mass from the process $Z^0 \to b'\bar{b}'$.

[#3] The simulation for $b' \to b\gamma$ and bg is implemented in ref. [19].

cluster algorithm [4]. The energy of each jet (E_j) is then determined from the solution of the four equations of energy–momentum conservation:

$$\sum_{j=1}^{4} E_j \boldsymbol{\beta}_j = 0 \quad \text{and} \quad \sum_{j=1}^{4} E_j = E_{\text{cm}} , \qquad (6)$$

where the velocity $\boldsymbol{\beta}_j$ is the vector sum of the momenta of all the particles in jet j divided by the sum of their energies. The direction of this vector sum defines the direction of the jet. The jet–jet invariant mass is then computed for all pairs of the four jets. Each pair of two jets is assigned to a b′ for that pairing which gives the smallest difference in invariant masses (ΔM) of the two pairs. Events are accepted if $|\Delta M| \leqslant 2\sigma_M$ where σ_M, the invariant mass resolution of two jets, is 5 GeV. The detection efficiency is 9%. With these event selection criteria, we observe 6 events in the data and expect 6.2 background events from the Monte Carlo simulation of the background process $Z^0 \to q\bar{q}(g)$ for 5 quarks. Since the 95% CL limit corresponds to 6.6 expected events, we exclude the branching ratio of $b' \to bg$ greater than 65% for b′ mass between 26.0 GeV and 46.0 GeV at 95% CL as shown in fig. 3 (right-hand side coordinate).

In conclusion, if the sum of the branching ratios of b′ decays into $c\ell\nu$ ($\ell = e, \mu, \tau$) by charged current and into bγ or bg by flavor-changing neutral current is assumed to be 100%, then the mass range of b′ from 26 GeV to 46 GeV is excluded at 95% CL. This result agrees well with refs. [15, 16].

5. Search for $Z^0 \to L^0\bar{L}^0$ from displaced vertices

The search for an L^0 using the isolated particle topology, as described in section 3, requires the mixing parameters $|U_{\ell L^0}|^2$ to be large enough that L^0 decays very close to the e^+e^- interaction point. The lifetime of the L^0 is inversely proportional to the mixing parameters $|U_{\ell L^0}|^2$ when L^0 couples to a lepton ℓ by

$$\tau(L^0 \to \ell^- X^+) = \left(\frac{m_\mu}{m_{L^0}}\right)^5 \frac{\tau_\mu \text{Br}(L^0 \to \ell^- e^+ \nu_e)}{f(m_{L^0}, \ell, X)\, |U_{\ell L^0}|^2} . \qquad (7)$$

The factor $f(m_{L^0}, \ell, X)$ is a phase-space correction, which is taken to be 1, as the smallest L^0 mass being considered is 20 GeV. $\text{Br}(L^0 \to \ell^- e^+ \nu_e)$ is taken to be 11% in this mass range. When the mixing to ℓ is small ($|U_{\ell L^0}|^2 \approx 10^{-10}$), the $Z^0 \to L^0\overline{L^0}$ signature is one or two vertices, separated from the e^+e^- interaction point, and with no charged particles coming from the interaction point. In the case of two vertices, these are expected to be collinear with the intersection point and on opposite sides of it. A search has been performed to look for such vertices.

Only charged particles having at least six TPC coordinates are considered for this analysis. A vertex finding algorithm is used to find all possible vertices of these charged particles in the event with momenta greater than 500 MeV/c. A vertex is defined if its χ^2 probability is at least 1%.

A possible $L^0\overline{L^0}$ pair is defined as any pair of vertices where the cosine of the angle θ in the $r\phi$ plane between the two vectors joining the vertices to the interaction point is less than −0.4. (i.e. $\theta > 114°$). If more than one such pair exists, the best pair is chosen on the basis of the largest number of charged particles used and the largest vertex–vertex opening angle in the $r\phi$ plane, in that order. If no such pair exists, the single vertex with the largest number of charged particles and lowest χ^2 is used. Also, if there are more charged particles in the best vertex than in the best pair, the single vertex topology is assigned to this event. Once a best pair or single vertex has been chosen, a final vertex fit is performed, where any leftover charged particles in the event are matched to the vertices already found, in increasing order of their effect on the vertex's χ^2, until a limit of 1% χ^2 probability is reached. A vertex is now required to have a minimum of three charged particles.

We require that $\cos\theta_v > -0.95$ (i.e. $\theta_v < 162°$) where θ_v is the angle, in the plane perpendicular to the beam axis ($r\phi$ plane), between the vector sum of the momenta of all the charged particles from the vertex and the direction from the interaction point to the vertex. The vertex must be well-contained within the TPC volume, i.e. $R_{r\phi} < 179$ cm and $|z_0| < 220$ cm where $R_{r\phi}$ is the distance between the vertex and the interaction point in the $r\phi$ plane and $|z_0|$ is the distance between the vertex and the interaction point along the beam axis.

To eliminate the background process $Z^0 \to q\bar{q}(g)$, the vertices found are required to have $R_{r\phi} > 1$ cm for a two-vertex topology and $R_{r\phi} > 7.8$ cm (the radius of the beam pipe) for a single-vertex topology.

In order to remove events from beam–gas and beam–pipe interactions, the sum of energies of all the charged particles belonging to one (in a one-vertex topology) or both (in a two-vertices topology) vertices in an event is required to be greater than 10 GeV.

To remove $Z^0 \to \tau^+\tau^-$ events which produce a displaced vertex because of poor vertex finding due to the highly collimated nature of these events, the cosine of the angle θ_{12} between the two fastest charged particles from the same vertex is required to be greater than -0.98 (i.e. $\theta_{12} < 169°$). Events with a vertex having $R_{r\phi}$ within 0.5 cm of the beam pipe, the ITC outer wall or the TPC inner wall are also rejected.

The majority of the cosmic ray background events are rejected by requiring a difference between the time of beam crossing and the time of energy deposition in the ECAL modules to be less than 200ns. This timing selection introduces less than 2.5% inefficiency in the $Z^0 \to q\bar{q}(g)$ data. Cosmic ray events are further reduced by examining the TPC coordinates between the vertex point and the interaction point. If $R_{r\phi}$ of the vertex is greater than $R_{r\phi}$ of the innermost TPC coordinate by more than 9 cm, the event is rejected. For a heavy L^0, low momentum charged particles may travel inwards, hence we only consider the innermost TPC coordinate of a charged particle with momentum greater than 9 GeV/c.

Applying the above event selection criteria to the data of 540 nb^{-1}, we find no candidate with a displaced vertex.

Monte Carlo simulated events for $Z^0 \to L^0\overline{L^0}$ are generated using the TIPTOP program [20] for different values of the mass and of the mixing parameter $|U_{\ell L^0}|^2$, taking into account the TPC systematics at their most pessimistic levels. The selection algorithm is applied to obtain the expected number of events at each point and a bicubic spline fit is then performed to obtain the contour (b) in the $|U_{\ell L^0}|^2$ versus M_{L^0} plane as shown in fig. 4. This corresponds to three expected events and gives the limit of the excluded region for $Z^0 \to L^0\overline{L^0}$ at 95% CL. This limit applies equally well to L^0 mixing to e, μ and τ, since the kinematic differences between these decays have a negligible effect upon the vertex finding algorithm. Superimposed in fig. 4 is the 95% CL limit contour (a) from the result of the search for prompt L^0 as described in section 3. Hence an L^0 is excluded up to a mass of 46.0 GeV with mixing parameters $|U_{\ell L^0}|^2$ as small as 10^{-13}. This is two orders of magnitude more sensitive than previously reported results [21].

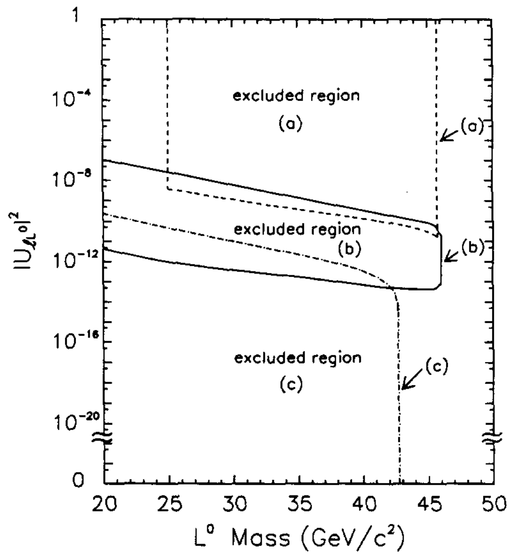

Fig. 4. The excluded regions at 95% CL for $Z^0 \to L^0\bar{L}^0$ in the $|U_{\ell L^0}|^2$ versus M_{L^0} plane from (a) the search for prompt L^0, (b) the search for long-lived L^0 from displaced vertices, and (c) the limit for long-lived L^0 from the total hadronic cross section measurement at the Z^0 peak. The bounded regions denote the areas of exclusion.

6. Mass limits on new quarks and new leptons from the total hadronic cross section measurement at the Z^0 peak

From the measurement of the peak hadronic cross section σ^0_{had} by the ALEPH Collaboration, the number of light neutrino species is found to be $N_\nu = 3.01 \pm 0.16$ [2]. This result can be used to set a mass limit on t, b′, $L^\pm$, stable ν_L and unstable L^0.

(i) $Z^0 \to \nu_L\bar{\nu}_L$. For $Z^0 \to \nu_L\bar{\nu}_L$, where ν_L is the stable fourth-generation neutrino, the result $N_\nu = 3.01 \pm 0.16$ excludes at 95% CL the region where

$$\Gamma_{\nu_L} > [(3.01 - 3.00) + 1.64 \times 0.16]\Gamma_{\nu_e} = 0.272\,\Gamma_{\nu_e}. \quad (8)$$

Here Γ_{ν_L} and Γ_{ν_e} are the partial widths for Z^0 decays into $\nu_L\bar{\nu}_L$ and $\nu_e\bar{\nu}_e$ respectively. The factor 1.64 corresponds to the one-sided 95% CL limit. The partial width $\Gamma_{1/2}$ for the Z^0 decaying into a pair of spin one-half particles is a function of the mass of the particles,

$$\Gamma_{1/2} = \frac{N}{24\pi} \frac{G_F M_Z^3}{\sqrt{2}} \beta[\tfrac{1}{2}(3-\beta^2)v^2 + a^2\beta^2] , \quad (9)$$

where N is the color factor, β is the velocity of each of these particles and v and a are the vector and axial vector couplings of the same particle to the Z^0. Using eqs. (8) and (9) the region where

$0 \leqslant M_{\nu_L} < 42.7$ GeV

is excluded at 95% CL.

(ii) $Z^0 \to L^+L^-$. For $Z^0 \to L^+L^-$ where $L^\pm \to \nu_L W^*$, the region where

$$\frac{\Gamma_{\rm had}}{\Gamma_{\rm tot}^2} = \frac{\Gamma_{5\,\rm quarks} + x\Gamma_{L^\pm}}{(\Gamma_{\rm SM} + \Gamma_{\nu_L} + \Gamma_{L^\pm})^2} < \frac{\Gamma_{5\,\rm quarks}}{(\Gamma_{\rm SM} + 0.272\Gamma_{\nu_e})^2} \quad (10)$$

is excluded at 95% CL. The coefficient 0.272 is obtained from eq. (8). Here x is the ratio of the detection efficiency for an $L^\pm$ to be identified as a hadronic event to the detection efficiency for hadronic event using the event selection criteria as described in ref. [1]. An event is accepted as a hadronic event if there are at least five charged particles and the total charged energy in the event is greater than 10% of the center-of-mass energy. The partial widths $\Gamma_{5\,\rm quarks}$ and $\Gamma_{\rm SM}$ take the standard model values with three generations: $\Gamma_5 = 1.737$ GeV and $\Gamma_{\rm SM} = 2.487$ GeV. Using eq. (9) and solving inequality (10) for M_{ν_L} in terms of $M_{L^\pm}$, we can exclude the full triangle $M_{\nu_L} < M_{L^\pm} < M_Z/2$, as shown in fig. 5, except for the small area near the top corner. In obtaining this excluded region the values of x are taken from Monte Carlo computations. The result is insensitive to x near the area where $M_{L^\pm}$ and M_{ν_L} are close in mass (x is near zero). Using the result given by subsection 6(i) above, the region where $M_{L^\pm} > M_Z/2$ and $M_{\nu_L} < 42.7$ GeV is excluded for all values of $M_{L^\pm}$ as shown in fig. 5. This result covers a much larger excluded region in the M_{ν_L} versus $M_{L^\pm}$ plane than previously reported [22].

For $Z^0 \to L^+L^-$ where the $L^\pm$ are stable, eq. (10) can be used to set limits on $M_{L^\pm}$ if we assume that $M_{\nu_L} > M_Z/2$ and hence it is not produced in Z^0 decay. In this case, in addition to Γ_{ν_L} being zero, x is also zero due to the fact that a two-charged-particle final state does not pass the hadronic event selection criteria. It follows from eq. (10) that the mass region

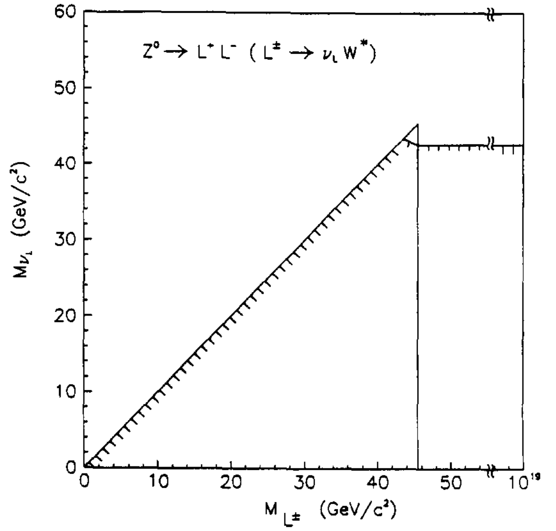

Fig. 5. The excluded regions at 95% CL for $Z^0 \to L^+L^-$ ($L^\pm \to \nu_L W^*$) in the M_{ν_L} versus $M_{L^\pm}$ plane. Note that the region where $M_{L^\pm} > M_{Z^0}/2$ and $M_{\nu_L} < 42.7$ GeV is excluded for all values of $M_{L^\pm}$.

$0 \leqslant M_{L^\pm} < 26.5$ GeV

for stable $L^\pm$ is excluded at 95% CL.

(iii) *$Z^0 \to t\bar{t}$, $b'\bar{b}'$ and $L^0\bar{L}^0$ (L^0 unstable and short-lived)*. For $Z^0 \to t\bar{t}$, $b'\bar{b}'$ and $L^0\bar{L}^0$, eq. (10) can be written as

$$\frac{\Gamma_{\rm had}}{\Gamma_{\rm tot}^2} = \frac{\Gamma_{5\,\rm quarks} + x\Gamma_j}{(\Gamma_{\rm SM} + \Gamma_j)^2} < \frac{\Gamma_{5\,\rm quarks}}{(\Gamma_{\rm SM} + 0.272\Gamma_{\nu_e})^2} , \quad (11)$$

where Γ_j = partial width of t, b′ or L^0 and x is essentially one. Applying eq. (9) to eq. (11), the mass regions $M_t < 31.3$ GeV, $M_{b'} < 39.4$ GeV and $M_{L^0} < 11.8$ GeV are excluded. Combining these results with the results from the direct searches described in sections 3 and 4, the following mass regions are excluded at 95% CL:

$0 \leqslant M_t < 45.8$ GeV ,

$0 \leqslant M_{b'} < 46.0$ GeV ,

$0 \leqslant M_{L^0} < 11.8$ GeV

and $25.0 \text{ GeV} < M_{L^0} < 45.7$ GeV .

(iv) $Z^0 \to L^0\bar{L}^0$ (*L^0 unstable and long-lived*). We consider an L^0 which has an average decay length larger than $R=390$ cm (the distance between the interaction point and the outer corner of the ECAL). This radius is chosen because it encloses the ITC, TPC and ECAL which are the essential elements for the hadronic event selection used in the measurement of total hadronic cross section [1,2]. Eqs. (7) and (9) and inequality (11) are used to determine the excluded region in the M_{ν_L} versus $M_{L^\pm}$ plane. The value x in eq. (11) is modified to be the product of the ratio of detection efficiencies as defined previously and the probability that a L^0 decays inside the radius R. To be conservative the ratio of detection efficiencies is set to one for decay inside R and zero outside. The excluded region in the $|U_{\ell L^0}|^2$ versus M_{L^0} plane at 95% CL limit is shown in fig. 4 (contour c). Combining the results given in sections 3 and 5, for 25.0 GeV $< M_{L^0} <$ 42.7 GeV all values of $|U_{\ell L^0}|^2$ are excluded.

7. Conclusion

A search for new heavy quarks (t and b′), new heavy charged ($L^\pm$) and unstable neutral leptons (L^0), has been performed using 542 nb^{-1} of data collected by the ALEPH detector. For $Z^0 \to t\bar{t}$, the t mass is excluded up to 45.8 GeV. For $Z^0 \to b', \bar{b}'$, the b′ mass is excluded up to 46.0 GeV taking into account both charged-current and flavor-changing neutral-current decays of the b′. For $Z^0 \to \nu_L\bar{\nu}_L$ and $Z^0 \to L^+L^-$ ($L^\pm \to \nu_L W^*$) where ν_L is a stable fourth-generation neutrino, results are deduced from the total hadronic cross section measurement at the Z^0 peak. The mass of ν_L is excluded up to 42.7 GeV. For $M_{\nu_L} <$ 42.7 GeV, the mass of $L^\pm$ is excluded for all values of $M_{L^\pm} > M_{\nu_L}$. Finally, for $Z^0 \to L^0\bar{L}^0$, the L^0 is excluded up to $M_{L^0}=45.7$ GeV with the mixing parameters $|U_{\ell L^0}|^2$, where $\ell = e, \mu$ or τ, down to 10^{-13} at this mass. For 25.0 GeV $< M_{L^0} <$ 42.7 GeV, all values of $|U_{\ell L^0}|^2$ are excluded. All limits are given at 95% CL.

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