Search for Excited Leptons at LEP

The OPAL Collaboration

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Abstract

Excited leptons have been searched for using data recorded by the OPAL detector at LEP. No evidence for such particles has been found. From the study of $e^+e^- \rightarrow l^+l^-\gamma\gamma$ events, lower limits on the masses of spin- $\frac{1}{2}$ excited leptons are found to be 44.9 GeV at 95% confidence level. From the study of $e^+e^- \rightarrow l^+l^-\gamma$ events, upper limits on their couplings are set up to l^* masses close to the mass of the Z^0 boson.

The existence of excited states of leptons and quarks is one of the natural consequences of composite models [1]. These models offer explanations for the existence of generations and the relations between leptons and quarks (i.e. similar SU(2) properties and the simple ratio of electric charges), which are not explained within the framework of the standard model. This paper presents a search for spin- $\frac{1}{2}$ charged excited leptons (l^* ; $l = e, \mu$ and τ) produced in e^+e^- collisions at LEP at centre of mass energies around the mass of the Z^0 boson and extends the previous limits [2,3] on the mass and the strength of the couplings. In this analysis an excited lepton is assumed to have spin- $\frac{1}{2}$ and to decay into an ordinary lepton and a photon with a 100% branching ratio. If the mass of an excited lepton is lighter than half of the available centre of mass energy, it can be pair-produced. The single-production of an excited lepton is also possible through the coupling l^*lV ($V = \gamma, Z^0$). In this case, a search can reach an l^* mass region close to the available centre of mass energy. To this purpose the processes $e^+e^- \rightarrow e^+e^-\gamma\gamma$, $e^+e^- \rightarrow e^+e^-\gamma$, $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$, $e^+e^- \rightarrow \mu^+\mu^-\gamma$, $e^+e^- \rightarrow \tau^+\tau^-\gamma\gamma$ and $e^+e^- \rightarrow \tau^+\tau^-\gamma$ have been studied. The process $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$, in which one of the electrons is scattered at small angles and escapes detection, has also been studied, because the single-production of e^* is dominated by t -channel photon exchange.

In this paper the Z^0 is assumed to couple to a spin- $\frac{1}{2}$ excited lepton pair in the same way as to ordinary lepton pairs. The lowest order pair-production cross section of excited leptons is given by:

$$\begin{aligned} \sigma_{e^+e^- \rightarrow l^*+l^{*-}} = & \frac{4\pi\alpha^2}{3s} \beta \frac{(3-\beta^2)}{2} \left\{ 1 + \frac{(1-4\sin^2\theta_W)^2}{8\sin^2\theta_W \cos^2\theta_W} \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} \right. \\ & \left. + \frac{(1-4\sin^2\theta_W)^2 + 1}{256\sin^4\theta_W \cos^4\theta_W} \left[(1-4\sin^2\theta_W)^2 + \frac{2\beta^2}{3-\beta^2} \right] \frac{s^2}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} \right\} \end{aligned}$$

where s is the square of the centre of mass energy, M_Z and Γ_Z are the mass and width of the Z^0 boson, θ_W is the weak mixing angle, and β is the velocity of the excited leptons in the final state:

$$\beta \equiv \sqrt{1 - \frac{4M_{l^*}^2}{s}}$$

The production cross section depends sensitively on the mass of the excited lepton, M_{l^*} , through β , and higher order radiative corrections substantially reduce this cross section.

The effective Lagrangian for the magnetic transition of spin- $\frac{1}{2}$ excited leptons to ordinary leptons is generally expressed as [4]

$$L_{eff} = \sum_{V=\gamma, Z^0} \frac{e}{\Lambda} \bar{l}^* \sigma^{\mu\nu} (c_V - d_V \gamma^5) l F_{\mu\nu}^V + h.c.,$$

where Λ is the composite mass scale and c_V and d_V are the coupling constants. The precise $g-2$ measurements imply $|c_V| = |d_V|$, and the absence of electric dipole moments for electrons and muons require that c_V and d_V have large real components. The coupling constants can be written as $c_\gamma = -\frac{1}{4}(f + f')$ and $c_{Z^0} = -\frac{1}{4}(f \cot\theta_W - f' \tan\theta_W)$ in terms of the weak mixing angle and free parameters f and f' [4]. In the following analysis we assume $f = f'$. In this scheme f/Λ is the only free parameter in the Lagrangian. According to the full formula of the differential cross section given in reference 4, a Monte Carlo program was made to generate single-production of spin- $\frac{1}{2}$ excited leptons.

We assume that the branching ratio $Br(l^* \rightarrow l\gamma)$ is 100%. Using the effective Lagrangian given above, the angular distribution of the decay $l^* \rightarrow l\gamma$ has a $(1 + \cos\theta)$ dependence with respect to the spin direction in the l^* rest frame [4]. This angular dependence was taken into account in the

Monte Carlo event generation. The decay of τ leptons was simulated using the JETSET Monte Carlo program [5].

The effect of initial state radiation was included in the event generator for the excited lepton pairs, whereas it was not included in that of the single-production. The overall reduction factor for the cross section of the single production (s -channel) was estimated to be 77%. The single-production cross section used in the following analysis includes this reduction factor.

The detailed description of the OPAL detector can be found elsewhere [6]. The components of the OPAL detector relevant to this analysis are described below. The trajectories and momenta of charged particles are measured by a central tracking detector in a uniform magnetic field of 0.435 T. It includes a precision vertex chamber, a large volume jet chamber which gives precise tracking information in the plane perpendicular to the beam direction and z -chambers for tracking in the plane parallel to the beam direction. The main tracking is done with the jet chamber, a drift chamber approximately four metres long and two metres in radius. It provides up to 159 measured space points along a track and covers the polar angular range $|\cos \theta| < 0.97$. The time-of-flight system (TOF) covers the region $|\cos \theta| < 0.82$ and consists of 160 scintillator bars. The barrel part of the electromagnetic calorimeter consists of 9440 lead glass blocks of 24.6 radiation lengths thickness pointing towards the interaction region. The barrel part covers the region $|\cos \theta| < 0.82$. The blocks are slightly tilted from a perfect pointing geometry to prevent photons from escaping through inter-block gaps. With the material in front (about 2 radiation lengths) and the current uncertainty in the gain calibration, the effective energy resolution is about 5% for 10 GeV and 3% for 45 GeV electrons. The position resolution is better than 5 mrad in the polar and azimuthal angles for electromagnetic showers of more than 10 GeV. The two endcaps of the electromagnetic calorimeter consist of 2264 lead glass blocks of 20 radiation lengths thickness, covering the polar angular range of $0.81 < |\cos \theta| < 0.98$. The iron return yoke of the magnet is instrumented with 9 layers of streamer tubes which provide hadron calorimetry and muon identification over nearly the whole solid angle. Muons are also identified in four layers of drift chambers surrounding the hadron calorimeter. The forward detector, used for the luminosity measurement, is composed of two identical elements placed around the beam pipe at either end of the central detector, each consisting of a lead-scintillator calorimeter and proportional tube chambers. They cover the polar angles between 40 and 150 mrad and 2π in azimuthal angle. The systematic error in the determination of the integrated luminosity is estimated to be 2.2% [7].

The data used in this paper were collected during an energy scan of the Z^0 resonance at centre of mass energies between 88.3 and 95.0 GeV. After applying quality cuts on the status of the electromagnetic calorimeter, jet chamber and forward detector, the integrated luminosity used in this analysis was 1.15 pb^{-1} .

The trigger of the OPAL experiment has a high degree of redundancy and high efficiency for the events under study in this paper. The trigger conditions relevant to this search were as follows.

- a) More than 6 GeV in the barrel or more than 10 GeV in one endcap was deposited in the electromagnetic calorimeter.
- b) At least two tracks with $|\cos \theta| < 0.7$ were found by the central detector trigger processor.
- c) Hits were found in at least 3 of the 4 layers of muon chambers and were associated in azimuthal angle with either a track or a TOF counter hit.
- d) More than 4 GeV was deposited in the barrel electromagnetic calorimeter and at least one track was found or one TOF counter was hit.

If any of the above conditions were satisfied, the event was recorded. The overall trigger efficiency is estimated to be more than 99% for each type of event discussed below.

The selection criteria for $e^+e^- \rightarrow e^+e^-\gamma$ ($e^+e^- \rightarrow e^+e^-\gamma\gamma$) events were:

- i) The number of electromagnetic clusters with more than 100 MeV of energy had to be less than 10.
- ii) At least three (four) energetic electromagnetic clusters were required, each with an energy greater than 10% of the beam energy and $|\cos \theta| < 0.70$.
- iii) The energy sum of the three (four) most energetic clusters had to exceed 80% of the centre of mass energy.
- iv) The opening angle between any two energetic clusters had to be greater than 10° .
- v) For $e^+e^- \rightarrow e^+e^-\gamma$ events, the sum of the opening angles between the three most energetic clusters had to be greater than 357° . This cut ensured that the events were planar.

Using these criteria, we selected a total of 29 events as $e^+e^- \rightarrow e^+e^-\gamma$ and zero events as $e^+e^- \rightarrow e^+e^-\gamma\gamma$. All the events selected as $e^+e^- \rightarrow e^+e^-\gamma$ were visually scanned and confirmed as clear $e^+e^- \rightarrow e^+e^-\gamma$ events. No $e^+e^- \rightarrow \gamma\gamma\gamma$ candidate was found in the angular region considered. The expected number of $e^+e^- \rightarrow e^+e^-\gamma$ events is 31.3 ± 0.6 , calculated by the BABAMC Monte Carlo program [8]. In the same data sample, we observed 746 collinear $e^+e^- \rightarrow e^+e^-$ events in the angular region $|\cos \theta| < 0.7$ selected by the cuts described in reference 7. The invariant mass of $e^\pm\gamma$ pairs was reconstructed using the energies and angles of the electromagnetic clusters, without requiring any further constraints on the kinematics. The mass resolution is calculated to be typically 1.0 GeV by Monte Carlo simulation. The reconstructed invariant mass distribution of $e^\pm\gamma$ pairs is shown in fig.1a together with the expectation from the BABAMC Monte Carlo program. The structure around $M_{e^\pm\gamma} = 30$ GeV, both in the real data and the Monte Carlo, is due to the kinematics of final state radiation and the angular and energy cuts imposed. The agreement between the measurement and the expectation is good.

To search for e^* single-production through t -channel photon exchange, $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$ events were selected using the following criteria.

- i) The number of electromagnetic clusters with more than 100 MeV of energy had to be less than 10.
- ii) At least two energetic electromagnetic clusters are required, each with an energy greater than 10% of the beam energy and $|\cos \theta| < 0.70$.
- iii) The energy sum of the clusters other than the two most energetic clusters had to be less than 10% of the beam energy.
- iv) The energy sum of the two most energetic clusters and the electron escaping into the beam pipe (i.e. $E_1 + E_2 + |E_1 \cos \theta_1 + E_2 \cos \theta_2|$, where E_i and θ_i were the energy and the polar angle of the energetic cluster i) had to exceed 80% of the centre of mass energy.
- v) The acollinearity angle between the two energetic clusters had to be greater than 10° .
- vi) The acoplanarity angle (acollinearity angle in the plane perpendicular to the beam direction) between the two energetic clusters had to be less than 10° .

- vii) One of the two energetic clusters had to be isolated from any charged tracks by at least 45° in azimuth, while the other had to be associated with at least one charged track.

Two events satisfied these criteria. The reconstructed invariant masses of the observed $e^\pm\gamma$ pairs were 40.8 GeV and 73.9 GeV. The expected number of events is 2.6 ± 0.2 estimated by the TEEGG Monte Carlo program [9] and is consistent with the observation.

The selection criteria for $e^+e^- \rightarrow \mu^+\mu^-\gamma$ ($e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$) events were:

- i) The number of high- P_t tracks was required to be between 2 and 6, where a high- P_t track was defined as a track with at least 36 of a possible 159 hits, satisfying: $P_t > 4$ GeV, $|d_0| < 2$ cm and $|z_0| < 70$ cm, where P_t is the momentum of the track in the plane transverse to the beam, d_0 is the distance of closest approach of the track to the beam axis and z_0 is the longitudinal displacement from the nominal interaction point at the point of closest approach to the beam.
- ii) The number of electromagnetic clusters with more than 100 MeV of energy had to be less than 10.
- iii) The energy sum of electromagnetic clusters had to be less than 75% of the centre of mass energy.
- iv) At least two high- P_t tracks, each with associated electromagnetic energy less than 4 GeV, were required in the polar angular region $|\cos \theta| < 0.70$.
- v) At least one (two) neutral electromagnetic cluster(s) with an energy larger than 10% of the beam energy and $|\cos \theta| < 0.70$ was (were) required.
- vi) Any opening angle between the high- P_t tracks and the neutral cluster(s) had to be greater than 10° .
- vii) The sum of the momenta of the two high- P_t tracks and the energy of the neutral cluster(s) had to exceed 50 GeV.
- viii) For $e^+e^- \rightarrow \mu^+\mu^-\gamma$ events, the sum of the opening angles had to be greater than 357° .

Using these criteria, we selected a total of 19 events as $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and one event as $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$. Through visual inspection, it was found that all the selected events had at least one clear track consistent with a muon in the hadron calorimeter or in the muon chambers. The expected numbers for the standard processes $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^- \rightarrow \tau^+\tau^-\gamma$ are 20.0 ± 1.4 and 1.8 ± 0.7 , respectively, calculated by the KORALZ Monte Carlo program [10]. The number of $e^+e^- \rightarrow \mu^+\mu^-$ events in the same data sample selected by the criteria given in reference 7 was 676. The invariant masses of $\mu^\pm\gamma$ pairs in $e^+e^- \rightarrow \mu^+\mu^-\gamma$ events were reconstructed from their opening angles only, assuming the kinematics of a three-particle final state. For μ -candidate tracks, the angles of associated electromagnetic clusters were used in the reconstruction. The typical mass resolution is estimated to be 0.8 GeV. The invariant mass distribution of $\mu^\pm\gamma$ pairs is shown in fig.1b together with the expectation from the KORALZ Monte Carlo program. There is a structure around $M_{\mu^\pm\gamma} = 30$ GeV, again due to the imposed angular and energy cuts. The agreement between the measurement and the expectation is good. Possible combinations of the invariant masses of $\mu^\pm\gamma$ pairs in the $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$ event are (26.0 GeV, 17.0 GeV) and (38.5 GeV, 32.6 GeV).

The event sample for the $e^+e^- \rightarrow \tau^+\tau^-\gamma(\gamma)$ analysis was obtained by applying the following cuts.

- i) The number of good tracks was required to be between 2 and 7, where a good track was defined as a track satisfying: $P_t > 0.05$ GeV, $|d_0| < 2$ cm and $|z_0| < 70$ cm.

- ii) The number of electromagnetic clusters had to be less than 10, where the energy thresholds for the clusters were chosen to be 100 MeV and 200 MeV for the barrel and the endcaps, respectively.
- iii) The total observed energy in the electromagnetic calorimeter had to be between 3 and 80% of the centre of mass energy, and the visible energy, defined as the sum of the electromagnetic energy and momenta of charged tracks, had to be between 18 and 120 % of the centre of mass energy.
- iv) The vertex position along the beam direction was required to be within 30 cm of the nominal beam crossing point, and at least one track should satisfy the condition $|d_0| < 0.5$ cm.
- v) $|\cos \theta_{mis}|$ had to be less than 0.95, where θ_{mis} was the direction of the missing momentum with respect to the beam axis, calculated from the energy vectors of the electromagnetic clusters.
- vi) The thrust axis, calculated with the electromagnetic clusters and the charged tracks, had to satisfy $|\cos \theta_T| < 0.85$, where θ_T was the angle between the thrust axis and the beam axis.
- vii) Events identified as $e^+e^- \rightarrow \mu^+\mu^-$ by the criteria described in reference 7 were rejected.

A total of 763 events remained after applying these cuts. From this τ -pair sample, we selected events which had at least three "jets". In this analysis, a "jet" could be either a single charged/neutral particle or a few charged/neutral particles, as expected from the τ decays. At first a cone of 15° half opening angle was defined along the direction of the highest energy particle, and the next highest energy particle in the cone was searched for. If a particle was found, the sum of the momenta of the two particles was used to define the centre axis of a new cone. This procedure was repeated until no more particle could be found in the cone. If the visible energy in the cone was greater than 10% of the beam energy, the cone was regarded as a "jet". If a jet was found, the same procedure was repeated using the remaining particles.

Using this "jet" finding method, we selected 31 three-jet events and no four-jet events. Out of the 31 events, four events without any isolated hard photon candidates were rejected through visual inspection. These events were classified as τ -pair events with no hard photons. We used the KORALZ Monte Carlo program to estimate the number of events from the radiative τ -pair production. The events generated by KORALZ were processed with the OPAL detector simulation program [11] and reconstructed in the same way as the real events. After applying the selection criteria, including the visual inspection, the expected number of events was found to be 23.5 ± 2.6 . The additional contribution from multihadronic events was estimated to be 2.4 ± 1.4 events by the JETSET Monte Carlo program [5]. Hence the observed 27 events are consistent with the expectation.

Applying the selection criteria to the events generated by the previously discussed Monte Carlo programs, we calculated numbers of events expected given our integrated luminosity and detection efficiency for single- and pair-production of excited leptons of various masses. In the Monte Carlo event generation the luminosity distribution at the different centre of mass energies at which data had been recorded was taken into account. We used our previously measured values of the Z^0 mass and width [7] in the Monte Carlo programs. Fig. 2 shows the expected number of events for each channel, where $f/\Lambda = 1/(300 \text{ GeV})$ is assumed for the single-production of excited leptons.

Comparing the numbers of observed events and expected events both for signal and background, we obtained limits on the masses and the coupling constants of $\text{spin-}\frac{1}{2}$ excited leptons. From the pair-productions, the lower limits on M_{e^*} , M_{μ^*} and M_{τ^*} are each 44.9 GeV at 95% confidence level, where the background yields are assumed to be zero. From the single-productions, upper limits on f/Λ are obtained as functions of the masses of the excited leptons. For e^* and μ^* , events which had an $l^\pm \gamma$ pair in the invariant mass region of $M_{l^*} - 2 \text{ GeV} < M_{l^\pm \gamma} < M_{l^*} + 2 \text{ GeV}$, were treated as

candidates. No such invariant mass cut was used for $\tau^\pm\gamma$ pairs and all the selected events (27 events) were treated as candidates. The 95% confidence level limits are shown in fig. 3. As seen in fig. 3a, the limit obtained from $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$ is better than that obtained from $e^+e^- \rightarrow e^+e^-\gamma$ in general. This is because of the large contribution of t -channel photon exchange to the single production of e^* and of the relatively low background. With the use of nearly the full data sample taken in 1989, the use of the process $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$, and high detection efficiency for each process (especially for τ^*), our limits are somewhat more stringent than the recently reported limits [3]. An indirect search for e^* is also possible by studying the QED reaction $e^+e^- \rightarrow \gamma\gamma$. At present, however, our limit from this reaction [12] is not strong enough to constrain M_{e^*} above the centre of mass energy due to small statistics, and at masses below the centre of mass energy the direct search yields more stringent constraints.

In summary, excited leptons have been searched for by studying the processes $e^+e^- \rightarrow e^+e^-\gamma\gamma$, $e^+e^- \rightarrow e^+e^-\gamma$, $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$, $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$, $e^+e^- \rightarrow \mu^+\mu^-\gamma$, $e^+e^- \rightarrow \tau^+\tau^-\gamma\gamma$ and $e^+e^- \rightarrow \tau^+\tau^-\gamma$. The observed events are consistent with the standard model expectations and no evidence for spin- $\frac{1}{2}$ excited leptons was found. From the study of $e^+e^- \rightarrow l^+l^-\gamma\gamma$ events, lower limits on the masses are found to be $M_{e^*} > 44.9$ GeV, $M_{\mu^*} > 44.9$ GeV, and $M_{\tau^*} > 44.9$ GeV at 95% confidence level. From the study of $e^+e^- \rightarrow l^+l^-\gamma$ events, upper limits on the l^*lV ($V = \gamma, Z^0$) couplings are set up to l^* masses close to the Z^0 mass.

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Figure 1: The reconstructed invariant mass distributions (points with error bars, two entries per event) for a) $M_{e^\pm\gamma}$ in $e^+e^- \rightarrow e^+e^-\gamma$ events and b) $M_{\mu^\pm\gamma}$ in $e^+e^- \rightarrow \mu^+\mu^-\gamma$ events compared with the Monte Carlo simulations (solid histograms). The dotted histograms show expected peaks corresponding to $f/\Lambda = 1/(300 \text{ GeV})$ and $M_{l^*} = 70 \text{ GeV}$.

Figure 2: The expected numbers of events from excited lepton productions after applying the selection criteria, shown as functions of the mass of excited leptons. a) number of events to be observed as $e^+e^- \rightarrow e^+e^-\gamma\gamma$ (solid curve), $e^+e^- \rightarrow e^+e^-\gamma$ (dashed curve) and $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$ (dash-dotted curve). b) number of events to be observed as $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$ (solid curve) and $e^+e^- \rightarrow \mu^+\mu^-\gamma$ (dashed curve). c) number of events to be observed as $e^+e^- \rightarrow \tau^+\tau^-\gamma\gamma$ (solid curve) and $e^+e^- \rightarrow \tau^+\tau^-\gamma$ (dashed curve). In the single-productions of excited leptons, $f/\Lambda = 1/(300 \text{ GeV})$ is assumed.

Figure 3: The upper limits on the coupling f/Λ as functions of the mass of the excited leptons. a) limits for e^* obtained from $e^+e^- \rightarrow e^+e^-\gamma$ (solid curve) and from $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$ (dash-dotted curve). b) limit for μ^* obtained from $e^+e^- \rightarrow \mu^+\mu^-\gamma$ (solid curve). c) limit for τ^* obtained from $e^+e^- \rightarrow \tau^+\tau^-\gamma$ (solid curve). The mass limits obtained from the pair-productions are shown by vertical lines.

Fig. 1

Fig. 2

Fig. 3