Experimental Limits on the Production of Excited Leptons and Stable Heavy Leptons

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The results are reported of a search for excited muons (μ^*) and electrons (e^*) and for a stable charged heavy lepton by measurements of the $e^+e^- \rightarrow \mu^+\mu^-$, $\mu^+\mu^-\gamma$, $\mu^+\mu^-\gamma\gamma$, and $\gamma\gamma$ final states. Excluded are large regions of the λ (coupling constant), M (mass) planes for spin- $\frac{1}{2}$ μ^* and e^* , and a new stable charged heavy lepton with mass < 14 GeV.

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Experiments over the last decade have established e^+e^- annihilation as a sensitive way to search for new leptons.¹ Searches for new τ -like leptons at PETRA have already been performed.²⁻⁵ There have been many theoretical discussions as to whether leptons are composite particles so that excited states exist.⁶ As PETRA has accumulated more than 50 000 nb⁻¹ up until the end of 1981, for center-of-mass energies up to $\sqrt{s} = 36.7$ GeV, it is now possible to extend the search for leptonic excited states and stable heavy leptons to a higher mass range.

Precise PETRA measurements of $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$ have been used to determine the weak neutral couplings g_V and g_A .⁷ Direct searches have also been performed for a neutral electron-related particle, for a stable charged particle produced inclusively in $e^+e^- \rightarrow$ hadrons, and for heavy-lepton production in muon-proton interactions.⁸

In this study we present the results of searches for an excited state of the muon ($\mu^* \rightarrow \mu + \gamma$) and of the electron ($e^* \rightarrow e + \gamma$), and for a stable charged heavy lepton (L^*) at PETRA. The MARK-J detector and methods for identifying muons, electrons, and photons have been presented previously.⁹

Search for μ^* .—The production of μ^* in the process $e^+e^- \rightarrow \mu^*\mu^* \rightarrow \mu^+\mu^-\gamma\gamma$ can be related to the ordinary pair cross section $\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \sigma_{\mu\mu}$ via the following relation: $\sigma_{\mu^*\mu^*} = \frac{1}{2}\sigma_{\mu\mu}(3\beta - \beta^3)|F(s)|^2$, where $\beta = P_{\mu^*}/E_{\mu^*}$ and $F(s)$ is the μ^* form factor. For pointlike μ^* , $F(s) = 1$. In our measurement of $\sigma_{\mu\mu}$ we only select two-muon events with acollinearity $< 20^\circ$ and for which both muons have momentum $P_\mu > \frac{1}{4}\sqrt{s}$. Our $\sigma_{\mu\mu}$ is within 3% of the QED prediction⁹ and to search for $\mu^*\mu^*$ events we select a two-muon sample with the same cuts. The production of $\mu^*\mu^*$ would significantly enhance our measurement of $\sigma_{\mu\mu}$. As shown in Fig. 1(a) the predicted number of events decreases with M . The detection efficiency, (predicted number of events)/ $[\sigma_{\mu^*\mu^*} \times (\text{integrated luminosity})]$, also decreases with M . From our 95%-confidence-level upper limit of nineteen $\mu^+\mu^-$ events from $e^+e^- \rightarrow \mu^+\mu^-$, we exclude production of a μ^* with $M < 10$ GeV [see Fig. 1(a)].

A higher-mass μ^* would lead to $\mu\mu\gamma$ final states from $e^+e^- \rightarrow \mu^*\mu$. The differential cross section for this process is¹⁰

$$\frac{d\sigma}{d\Omega} = \lambda^2 \alpha^2 \frac{(s - M^2)^2}{s^3} [(s + M^2) - (s - M^2)\cos^2\theta], \quad (1)$$

FIG. 1. (a) Predicted number of muon pairs coming from the process $e^+e^- \rightarrow \mu^*\mu^* \rightarrow \mu^+\mu^-\gamma\gamma$ as a function of M . The horizontal line corresponds to the 95%-confidence-level (C.L.) upper limit from our measurement of $e^+e^- \rightarrow \mu^+\mu^-$. A μ^* with $M < 10$ GeV is excluded. (b) 95%-confidence-level upper limit on $\sigma_{\mu^* \mu} / \sigma_{\mu \mu}$ as a function of the μ^* mass M . (c) 95%-confidence-level upper limit on λ^2 as a function of M .

where M is the mass of μ^* and λ is the coupling defined by the following phenomenological interaction Lagrangian:

$$L_{\text{eff}} = \lambda e \bar{\psi}_{\mu^*} \sigma_{\beta\delta} \psi_{\mu} F^{\beta\delta} + \text{H.c.}$$

($F^{\beta\delta}$ is the electromagnetic field tensor).

If the μ^* is massive and decays rapidly via $\mu^* \rightarrow \mu\gamma$, $\mu^*\mu$ events would be mixed with the radiative production of muon pairs $e^+e^- \rightarrow \mu^+\mu^-\gamma$, and with a small contribution of $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ production where two muons and an electron are observed in our detector. We use the following

selection criteria: (i) one muon with $P_t \gtrsim 1.5$ GeV, which penetrates the detector iron and reaches the outer drift chamber, and a second muon with $P_t \gtrsim 0.8$ GeV, which reaches the trigger counter midway through the iron; (ii) $E_{\text{em}} \geq 20\% E_{\text{beam}}$; (iii) $\theta_{\text{em}} \geq 25^\circ$; and (iv) $|\vec{P}_{\mu_1} + \vec{P}_{\mu_2} + \vec{P}_\gamma| < 0.25\sqrt{s}$ (momentum balance); where E_{em} and θ_{em} are the magnitude and angle (with respect to the beam axis) of the electromagnetic energy measured in the shower counters. With this selection our Monte Carlo calculation predicted 116 events coming from $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^- \rightarrow e^+e^- + \mu^+\mu^-$.¹¹ We observed 108 events in our data with $\int L dt = 43 \text{ pb}^{-1}$ for $\sqrt{s} > 30$ GeV.

A Monte Carlo study of the μ^* mass resolution ΔM was performed by computing the two $\mu\gamma$ mass combinations from the muon and photon angles in the final state of $e^+e^- \rightarrow \mu^*\mu \rightarrow \mu\mu\gamma$. We found $\Delta M \leq 1$ GeV, independent of M .

The good $\mu\gamma$ mass resolution was exploited by computing $n(M)$, the maximum number of events that can be attributed to a μ^* of mass M , where the measured mass lies in the range from $M - 1$ to $M + 1$ GeV. We computed the corresponding acceptance, $A(M)$, and found upper limits for the production cross section of $\mu^*\mu$:

$$\sigma_{\mu^* \mu} < \frac{n(M)}{(\int L dt) A(M)}$$

(95% confidence level).

Our limits on $\sigma_{\mu^* \mu} / \sigma_{\mu \mu}$ are shown in Fig. 1(b) as a function of M . As seen for $M < 30$ GeV, the production cross section for μ^* , $\sigma_{\mu^* \mu}$, is $< 1\%$ of $\sigma_{\mu \mu}$. From Eq. (1) the limit can also be expressed in terms of λ^2 , as shown in Fig. 1(c).

We therefore see that if the muon is a composite particle, the splitting between ground state and first excited state must be very large: $M/m_\mu \gtrsim 10^2$ (95% C.L.). The interaction binding the constituents must then be very different from the known interactions.

Search for e^* .—If there is an excited state of the electron, the process $e^+e^- \rightarrow \gamma\gamma$ would be modified by the exchange of a virtual e^* in the t channel.^{5,10,12} As in the case of the μ^* , the differential cross section¹⁰ depends on the coupling λ' and on the mass M' of the e^* , where λ' is defined by the following interaction Lagrangian:

$$L_{\text{eff}} = (\lambda' e / 2M') \bar{\psi}_{e^*} \sigma_{\mu\nu} \psi_e F^{\mu\nu} + \text{H.c.}$$

Electrons are distinguished from photons by the presence of tracks in the drift tubes, which cover $\sim 75\%$ of φ (the corners are not covered). The acceptance in $\cos\theta$ is uniform and is $(75 \pm 1)\%$

FIG. 2. (a) Differential cross section scaled by s ($\sqrt{s} > 33$ GeV) for the process $e^+e^- \rightarrow \gamma\gamma$, as a function of $\cos \theta$. θ is the angle of the photons with respect to the beam axis. (b) 95%-confidence-level upper limit on the coupling λ' as a function of the mass of the e^* . A systematic error of 3% on the luminosity measurement and a point-to-point systematic error of 3% were used in the fit.

for $0.2 \leq |\cos \theta| \leq 0.8$. As shown in Fig. 2(a), our measurement of the differential cross section agrees quite well with the prediction of pure QED including radiative corrections,¹¹ and we are therefore able to set limits on λ' and M' . For example, if $\lambda' = 1$ an e^* of mass $M' = 10$ GeV will enhance the measured $\gamma\gamma$ rate at $\cos \theta = 0.25$ by a factor of 30.

By making a two-parameter fit (λ', M') to our data, using the exact form of the cross section derived in Ref. 10, we obtain a 95%-C.L. upper limit on λ' as a function of M' . Figure 2(b) illustrates our result. We find that for $\lambda' = 1$, the lower limit on M' is 58 GeV.

We therefore conclude that if an e^* exists, its mass must be large or its coupling strength very small: $M'/m_e \geq 10^5$ for $\lambda' = 1$.

Search for a stable heavy lepton.—There have been many conjectures concerning the existence of a fourth family of leptons.¹³ One interesting

FIG. 3. The expected number of events combined from the processes $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow L^+L^-$ as a function of the mass of the $L^\pm$. The 95%-confidence-level limit shown corresponds to our measurement of 57 events at $\sqrt{s} = 36$ GeV. The inset displays the predicted momentum for the $L^\pm$ as a function of its mass at $\sqrt{s} = 36$ GeV.

possibility is that the neutrino in this fourth family could be more massive than the charged lepton, thus leaving this new heavy lepton relatively stable.¹⁴ Such a new lepton would be pair produced in e^+e^- annihilation via $e^+e^- \rightarrow L^+L^-$, and the events would have an appearance similar to muon pair production with a suitably altered momentum spectrum.

The event selection criteria are similar to those for our muon pair selection, namely, two particles must reach the outermost drift chambers within 10 nsec of the beam crossing time; each particle's momentum must be $> 50\% E_{\text{beam}}$; the acollinearity angle between the particle directions must be $< 20^\circ$.

The number of events expected with these selection criteria is shown in Fig. 3 as a function of the $L^\pm$ mass. The prediction for the $L^\pm$ momentum spectrum as a function of $L^\pm$ mass is shown in the inset. In these predictions, ionization energy loss in the detector¹⁵ and initial-state radiative corrections (to order α^3) were taken into account. It should be noted that the genuine muon pairs are included in the expected number of events. Our measurement of 57 events in the energy range from 36 to 36.7 GeV corresponding to a time-integrated luminosity of 1854 nb^{-1} gives a 95%-confidence-level lower limit of 14 GeV for the mass of $L^\pm$.

As a consistency check we also studied the timing of all particles reaching our trigger count-

ers situated 1.35 m from the interaction region. We found no event for which the particles were more than 4 ns later than expected for a muon. This excludes stable particles with a mass between 9 and 14 GeV at the 95% confidence level, confirming our previous result. In order for an L^* to reach the exterior drift chambers, its lifetime in the laboratory frame should be $\gg 4$ ns.

We have searched for the production of new leptons in e^+e^- annihilation events. Our search for an excited state of the muon μ^* yields a lower limit on the μ^* mass, M , of 10 GeV, and we exclude a large region of the μ^* mass and coupling constant plane up to $M \approx 30$ GeV at the 95% confidence level. For an excited electron with mass M' and coupling λ' , we rule out a large section of the $M'-\lambda'$ plane, and find that for a coupling constant equal to that of the electron, $M' > 58$ GeV. Finally, we exclude the existence of a stable charged heavy lepton with a mass less than 14 GeV.

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