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Search for excited electrons using the ZEUS detector

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This paper reports a search for excited electrons at the HERA electron-proton collider. In a sample corresponding to an integrated luminosity of $26\,\mathrm{nb}^{-1}$, no evidence was found for any resonant state decaying into $e^-\gamma$, νW^- or e^-Z^0. Limits on the coupling strength of an excited electron have been determined for masses between 45 and 225 GeV. This study also reports the observation of the wide-angle $e\gamma$ Compton scattering process.

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1. Introduction

In the standard model of electroweak and strong interactions, leptons and quarks, together with gauge bosons, are the fundamental constituents of matter. Although this model has been very successful in describing experimental data, it does not predict the fermion masses and other parameters. Observation of a new substructure would require an extension of the standard model, which might relate some of these parameters to more fundamental quantities. The search for excited electron states (e^*) is a natural way to investigate such a substructure in the fermionic sector. Various limits on the substructure scale have been derived mainly from e^+e^- experiments. A recent compilation is found in ref. [1].

Models of e^* production have been proposed [2,3] but so far there has been no experimental evidence supporting the existence of an e^* [4,5]. Results from LEP experiments [5] restrict $e^* \to e\gamma$ couplings for e^* masses up to the Z mass. Complementary limits, due to virtual contributions, arise from data on $e^+e^- \to \gamma\gamma$, νe scattering, and electron gyromagnetic ratio measurements [2–6]. It should be noted, however, that calculations of such virtual effects are quite sensitive to model dependent assumptions.

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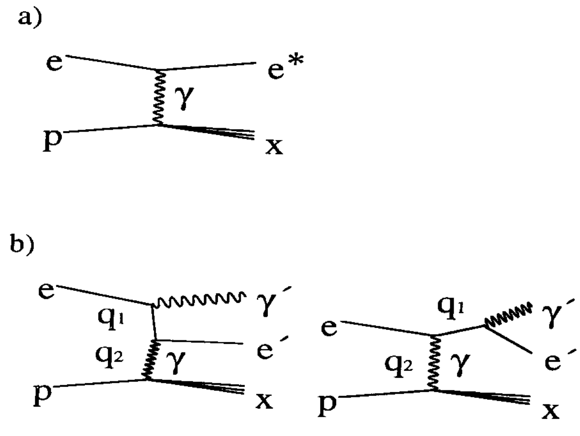

Fig. 1. Feynman diagrams describing: (a) e^* production through t-channel photon exchange and (b) wide-angle Compton scattering, defined as $q_2^2 \approx 0$ GeV^2 and q_1^2 finite.

At the HERA electron-proton collider, excited electrons with masses up to the present kinematic limit of 296 GeV would be directly produced via the process $ep \to e^*X$ (fig. 1a). This high centre of mass energy allows a search not only for the decay mode $e^* \to e\gamma$, but also for the decay modes $e^* \to \nu W$ and $e^* \to eZ$, which have not been investigated prior to HERA.

This paper presents results obtained by the ZEUS collaboration using data corresponding to an integrated luminosity of 26 nb^{-1}, from collisions of 26.7 GeV electrons with 820 GeV protons. We have searched for resonances in the $e\gamma$, νW, and eZ final states. Such a search has also been performed by the H1 collaboration [7]. As part of this study, we observed events due to wide-angle Compton scattering (hereafter referred to merely as Compton scattering), $\gamma e \to \gamma e$ (fig. 1b). These events are topologically similar to the $e^* \to e\gamma$ reaction.

2. Production and decay of excited electrons

The occurrence of two energetic electromagnetic showers isolated from hadronic activity is characteristic of an $e^* \to e\gamma$ event, while the signature of an excited electron decaying into final states containing a heavy gauge boson is large transverse energy. The eZ decay mode would contain an energetic electron, while the $e^* \to \nu W$ channel would have missing transverse momentum from the undetected neutrino.

Although this search would uncover *any* resonant e^* state of appropriate coupling, independent of its spin and other dynamic properties, we have used a specific phenomenological model of excited leptons [2] to extract limits on coupling strengths. In this model, the e^* is assumed to be a spin-1/2 state which couples magnetically to electroweak gauge bosons and first-generation leptons. The interaction in its most general form is characterized by a compositeness scale Λ and two coupling parameters, $c_{VL\ell}$ and $d_{VL\ell}$. Here V denotes the gauge boson (γ, W, Z), L denotes the excited lepton (e^*, ν_e^*), and ℓ denotes the lepton (e, ν_e). Contributions from the Z and W propagators to excited lepton production cross sections are negligible for the present integrated luminosity. The e^* production cross-section through t-channel photon exchange is then given by

$$\sigma(\mathrm{ep} \to \mathrm{e}^*\mathrm{X}) = \frac{|c_{\gamma\mathrm{e}^*\mathrm{e}}|^2 + |d_{\gamma\mathrm{e}^*\mathrm{e}}|^2}{\Lambda^2}\sigma_0(m_{e^*}),$$

where σ_0, a function of the e^* mass, is the result of an integration over phase space of known coefficients and the proton structure functions. For e^* masses between 45 and 225 GeV, σ_0 varies between 3.6×10^6 and 2.4×10^4 pb·GeV^2, respectively.

Monte Carlo samples of e^* production were generated, using the HEXF generator [8], according to the cross-section of ref. [2]. Since the production of an e^* occurs predominantly by t-channel photon exchange in this model, the proton often scatters quasi-elastically, producing little hadronic energy outside the beampipe. In the deep inelastic region ($Q^2 > 5$ GeV^2) we used the structure function parametrization of MTB1 [9] while for $Q^2 < 5$ GeV^2 we used the parametrization of Brasse et al. [10]. The dependence of the cross section on the structure function parametrization is weak and is given in section 8. The effects of initial state radiation were included [11]. For the inelastic contributions to e^* production, LEPTO 6.1 [12] was used to model the QCD effects of multiple gluon emission and hadronization of the final state was simulated by JETSET 7.3 [13].

The principal background in our search for excited electrons comes from deep-inelastic scattering events (DIS). For $e^* \to e\gamma$ transitions, high energy Compton scattering is an additional source of background. Several other contributions, including photoproduction, where a quasi-real photon has interacted with the proton (γp photoproduction) and deep inelastic Compton scatters, where a photon is radiated from a quark line, were found from Monte Carlo studies to be negligible after the application of all cuts. The two main backgrounds were studied in detail using a Monte Carlo simulation. Compton events were generated by the COMPTON 2.0 program [14] using HERWIG [15] for fragmentation of the hadronic system. DIS events with radiative corrections were generated using HERACLES [16] with the MRSD0 structure functions [17]. Hadronization was simulated by the parton shower model, LEPTO 5.2 [12]. The response of the detector was studied using a GEANT [18] based simulation program. Monte Carlo events with a valid trigger signature were subject to the same reconstruction algorithms and selection procedures as were used for the data sample.

3. Apparatus

The HERA collider and the ZEUS detector are described elsewhere [19]. In this analysis, the principal detector components used are the high resolution calorimeter, the central tracking detector, and the luminosity monitor. The calorimeter provides energy and timing measurements [20,21] and covers the polar angle range $2.6° < \theta < 176.1°$, where $\theta = 0°$ is the proton beam direction. The central tracking detector [22] was used to measure charged particle trajectories in order to reconstruct a vertex for each event. The luminosity was obtained from the rate of bremsstrahlung, $\mathrm{ep} \to \mathrm{ep}\gamma$ [23].

4. Initial data selection

This analysis follows the trigger and initial data selection described previously in ref. [24]. This section reviews the main steps. The trigger was based mainly on information from the electromagnetic sections of the calorimeter which had a typical energy threshold $\leqslant 2.5$ GeV in a single trigger tower.

For e* decays to eγ, eZ $\rightarrow$ e$q\bar{q}$, or e$^-$Z $\rightarrow$ e$^-$e$^+$e$^-$ we used the neutral-current (NC) sample, for which one requirement was an electromagnetic shower in the calorimeter of at least 10 GeV. A further requirement was that the longitudinal energy variable, δ, have a value above 20 GeV. This variable is defined as $\sum E_i(1-\cos\theta_i)$, where E_i is the energy deposit in a calorimeter cell at polar angle θ_i. The sum runs over all cells. The nominal value of δ, expected from momentum conservation, is twice the electron beam energy.

We searched for e* decays to νW or eZ $\rightarrow$ e$\nu\bar{\nu}$ in the final charged current (CC) sample. The principal requirement here was that the missing momentum transverse to the beamline exceed 10 GeV. Remaining cosmic ray triggers were removed from the sample by visual scanning.

For both the NC and the CC samples, beam gas background was rejected by demanding a vertex and calorimeter timing consistent with an ep collision. The remaining contamination is mainly from γp photoproduction; it was reduced by requiring that no electron be observed in the luminosity monitor.

After these selections, 4496 NC events and 2 CC events remained.

5. Analysis of the eγ inclusive final state

The eγ final state is characterized by two isolated electromagnetic showers in the calorimeter. A total of 170 events from the NC sample have a second electromagnetic shower with an energy of at least 2 GeV. Three of these have a third cluster with energy exceeding 2 GeV. The ambiguity in these three events was resolved by assigning to the e* the two electromagnetic showers whose combined transverse momentum was most consistent with zero transverse momentum of the e*.

5.1. Search for high mass eγ states

The sample of 170 events with more than one electromagnetic shower was used to search for the decay e* $\rightarrow$ eγ. To reduce γp photoproduction background further, and also to reject events with a large energy loss in the material close to the beam pipe, δ was more tightly constrained to be between 30 and 60 GeV. We required that the polar angles of both electromagnetic showers be less than 155° since Monte Carlo studies showed that this reduced the DIS background by a factor of 30 and the Compton background by a factor of 20. As can be seen from the distributions of fig. 2a, the effect of this polar angle cut on the e* acceptance is small. The overall detection efficiency for e* $\rightarrow$ eγ depends on the e* mass. It is typically about 75% for high masses and drops to 65% at m_{e^*} = 45 GeV.

After these cuts, 7 data events remained (fig. 2b). The expected background is 5.6 DIS and 0.8 Compton events. No data event with $m_{e\gamma}$ above 45 GeV survives; 0.25 DIS events and 0.1 Compton events are expected with $m_{e\gamma} > 45$ GeV.

There is no evidence for an eγ resonance. An upper limit, $\sigma^{\max}_{\text{inclusive}}(e\gamma)$, on the inclusive production cross-section for two electromagnetic showers with 45 GeV $< m_{e\gamma} <$ 296 GeV can be calculated following the prescription of the Particle Data Group [25]. We obtain an upper limit of $\sigma^{\max}_{\text{inclusive}}(e\gamma)$ = 180 pb at the 95% confidence level by assuming 65% detection efficiency and Poisson statistics and also including the effects of systematic errors.

5.2. Observation of high energy Compton scattering

The presence of two electromagnetic showers, the signal for e* $\rightarrow$ eγ, is also characteristic of eγ Compton events. In order to verify that ZEUS can reconstruct such events, we have searched for quasi-elastic Compton scatters.

The Compton signal was enhanced by removing the cut on the polar angle of the electromagnetic showers, requiring instead that the two showers contain more than 90% of the calorimeter energy. Furthermore, we required that the difference in azimuthal angle between the two showers be larger than 150°. After the cuts, 15 of the 170 events remained, with the $m_{e\gamma}$ distribution shown in fig. 2c. A Monte Carlo simulation predicts 2.3 events due to deep-inelastic scattering and 9.1 Compton events, in agreement with observation. The difference in polar angle between the two electromagnetic clusters is shown in fig. 2d. The overlaid distributions obtained from Compton and DIS Monte Carlo samples strongly supports the interpretation of these data as Compton events. The distribution of the energy sum of the two electromagnetic clusters peaks near the electron beam energy, as expected. The ob-

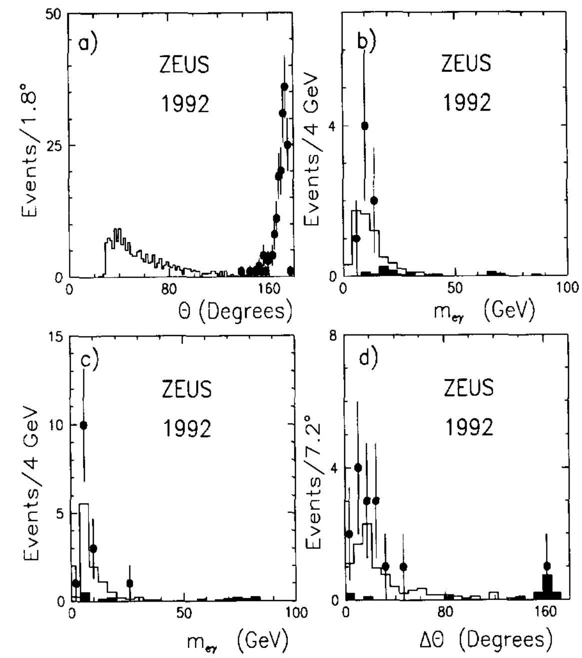

Fig. 2. (a) Distribution of the larger polar angle of the two showers in the e* →eγ search sample before the application of the polar angle cut. The histogram represents the same distribution for an e* with a mass of 250 GeV (Monte Carlo), normalized to the same number of events as the data. (b) Invariant eγ mass distribution of the e* search sample (data points). The open (filled) histogram represents the distribution obtained from the Compton and DIS (Compton alone) Monte Carlo studies, normalized to data luminosity. (c) Invariant eγ mass distribution of the Compton sample. The open (filled) histogram represents the distribution obtained from the Compton and DIS (DIS alone) Monte Carlo studies, normalized to data luminosity. (d) Difference in polar angle between the two electromagnetic showers. The open (filled) histogram represents the distribution obtained from the Compton (DIS) Monte Carlo studies, normalized to data luminosity.

served rate of Compton events agrees with theoretical expectations.

6. Analysis of the eZ final state

Three decay modes of the Z boson were sought as signals for $e^* \to eZ$ transitions. A final state with three electromagnetic showers is characteristic of the decay chain $e^{*-} \to e^-Z \to e^-e^+e^-$. Three events of the NC sample satisfied this condition, but the highest combined energy for any pair of electromagnetic showers in these events is 21 GeV, inconsistent with a $Z \to e^+e^-$ decay. Neither of the events in the CC sample contained an isolated electron and they are, therefore, inconsistent with the decay chain $e^* \to eZ \to e\nu\bar{\nu}$.

While there are negligible backgrounds in the $e^-e^+e^-$ and $e\nu\bar{\nu}$ final states, increased sensitivity to eZ production can be achieved by searching for decays of Z bosons into quark–anti-quark pairs, which have a much higher branching ratio, $\mathcal{B}(Z \to q\bar{q}) \approx 70\%$. Starting from the NC sample described in section 4, we selected events with exactly one isolated electron candidate. As before, cuts on the longitudinal energy variable, 30 GeV < δ < 60 GeV, and the electron polar angle, $\theta_e < 155°$, were used to reduce the backgrounds. The hadronic decay of a Z boson would deposit large transverse energy, $E_\perp^Z = \sum E_i \sin\theta_i - E_\perp^{\text{electron}}$, where the sum runs over all calorimeter cells. Monte Carlo studies indicated that the cut $E_\perp^Z > 50\ GeV$ removes 99% of the backgrounds while retaining 73% (98%) of the signal events at m_{e^*} = 100 GeV (290 GeV).

Only one event satisfied our selection criteria, while 4.6 DIS events (3.2 events with m_{eZ} > 120 GeV) were expected from Monte Carlo. Thus, there is no evidence for an eZ resonance. Including the $Z \to q\bar{q}$ branching fraction, the detection efficiency for the eZ decay mode is typically about 45%, falling below 40% at m_{eZ} = 120 GeV.

We obtain an upper limit on the inclusive eZ production cross section of 350 pb at the 95% confidence level for eZ invariant masses between 120 and 296 GeV by assuming an overall acceptance of 40% and Poisson statistics and also including the effects of systematic errors.

7. Analysis of the νW final state

Since this final state would have missing transverse momentum from the undetected neutrino, we use the CC sample defined in section 4 to search for the decay $e^* \to \nu W$. The absence of an electron in either event of the charged current sample implies the absence of the decay $e^* \to \nu W \to \nu\bar{\nu}e$. In order to set a limit for the channel $e^* \to \nu W$, the hadronic W decay modes were used. Only one additional cut was imposed on the CC sample. Candidate events were required to have a transverse energy deposition $E_\perp^W > 50$ GeV, where $E_\perp^W = \sum E_i \sin\theta_i$. A Monte Carlo study shows that 62% (90%) of the signal events at e* masses of 100 (250) GeV pass this cut while the background is reduced by a factor of 3.

Of the two CC events, one, for which the e* candidate invariant mass is (225 ± 28) GeV, survived this restriction. According to a Monte Carlo simulation, 0.1 DIS events are expected above a mass of 100 GeV. Including the W → q$\bar{q}$ branching fraction, the detection efficiency for the νW decay mode is typically about 55%, falling below 45% at $m_{\nu W} = 110$ GeV. There is, then, no strong evidence for a νW resonance.

We obtain an upper limit on the inclusive νW production cross section of 400 pb at the 95% confidence level for νW invariant masses between 110 and 296 GeV by assuming an overall acceptance of 45% and Poisson statistics and also including the effects of systematic errors.

8. Systematic uncertainties

Contributions to the systematic error in the e* coupling strength arise from uncertainties in the detection acceptance (ϵ), σ_0 as defined in section 2, and the integrated luminosity ($\mathcal{L}$).

The systematic errors on the overall acceptances of the final states sought in this analysis were estimated to be 10%. This includes uncertainties in the energy scale, Monte Carlo statistics, and the interpolation of the acceptances between the generated e* mass values. The effect on the acceptance of using different proton structure functions was found to be negligible.

The systematic uncertainty in the calculation of σ_0 was estimated at 7% by using different parametrizations of the proton structure functions [9,26]. It also includes smaller uncertainties in the calculation of the radiative corrections. The error of the luminosity measurement was estimated to be 10%.

Combining these contributions in quadrature results in an overall systematic error of 16%.

9. Extraction of the e* coupling limit

For all decay modes studied, the number of signal

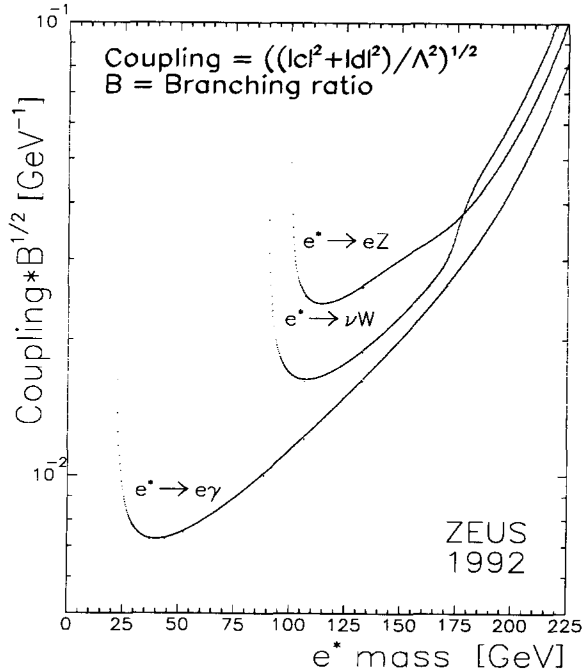

Fig. 3. 95% confidence level upper limits on the product of the coupling and the square root of the branching ratios $[(|c_{\gamma e^* e}|^2 + |d_{\gamma e^* e}|^2)^{1/2}/\Lambda]\mathcal{B}^{1/2}$ for eγ, eZ, and νW final states. To compare with published limits [5,7], which assume $|c_{\gamma e^* e}| = |d_{\gamma e^* e}|$, one must divide our limits by $\sqrt{2}$.

events remaining after our selection cuts is consistent with the estimated background. As a function of e* mass, limits on the product of the coupling and the square root of the branching ratio at the 95% confidence level were extracted assuming Poisson statistics, a Gaussian e* resolution function, and a background distribution determined by Monte Carlo. The limits are insensitive to details of the resolution functions and background distributions used. This procedure extends the method described in ref. [25]. It includes the probability that the experimental mass distribution arose from an e* of the postulated mass together with the expected background. The systematic uncertainties in σ_0, ϵ and $\mathcal{L}$ were included in the determination of the upper limits. Using the notation introduced in section 2, we obtained the limit from

$$\frac{(|c_{\gamma e^* e}|^2 + |d_{\gamma e^* e}|^2)^{1/2}}{\Lambda}\mathcal{B}^{1/2} = \sqrt{\frac{N}{\epsilon\mathcal{L}\sigma_0}},$$

Table 1
Numbers of events and expected backgrounds for the channels studied in this analysis. The efficiency is for an e* decay into the corresponding channel; the efficiency value varies as a function of the e* mass. No event was found corresponding to the decay chains $e^- Z \to e^- e^+ e^-$, $eZ \to e\nu\bar{\nu}$, and $\nu W \to \nu\bar{\nu}e$. $\sigma^{max}_{inclusive}$ is the 95% confidence level upper limit on the production cross section of the search channel state.

Search channel	Mass range (GeV)	Number of events	Expected background	Efficiency	$\sigma^{max}_{inclusive}$ (pb)
$e\gamma$	45-296	0	0.35	65-78%	180
eZ	120-296	1	3.2	40-50%	350
νW	110-296	1	0.1	45-62%	400

where N is the upper limit on the number of events consistent with our observations, and B is the branching ratio. Fig. 3 shows the 95% confidence limits on the product of the coupling and the square root of the branching ratio for each of the three e* decay channels as a function of m_{e^*}. These limits are shown for excited electrons up to $m_{e^*} = 225$ GeV. For masses greater than 225 GeV, the limit on the coupling becomes sufficiently weak that the calculation of σ_0 in our model-dependent analysis is no longer valid [2].

Our limits, like comparable results from the H1 Collaboration [7], explore the high mass region which was inaccessible to direct searches prior to HERA. For $m_{e^*} < m_Z$, the most stringent limits on the e* coupling constant are set by the LEP experiments [5]. Measurements of the Z width rule out excited electrons below a mass of 30.2 GeV. Searches for e* $\bar{e}^*$ pairs from from Z decays exclude e* masses below 45 GeV. In the region just below the Z mass, the LEP limits from a direct search for Z→e*e followed by the decay e* →eγ are about an order of magnitude more stringent than the current HERA results.

10. Summary

The ZEUS collaboration has searched in a model-independent way for resonances in the eγ, νW, and eZ systems. With an integrated luminosity of 26 nb^{-1}, we see no evidence for such resonances with invariant masses below 296 GeV. We have set 95% confidence level upper limits of 180, 350, and 400 pb for the inclusive cross-sections of eγ production above a mass of 45 GeV, eZ production above a mass of 120 GeV, and νW production above a mass of 110 GeV, respectively (see table 1). Limits on ee*γ couplings for e* masses between 45 and 225 GeV have been determined. We also report the observation of high energy γe Compton scattering in an ep experiment.

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