SIGNALS OF EXCITED QUARKS AND LEPTONS ^{*)}

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ABSTRACT

e^+e^- annihilation to two photons (including beam polarization) and quark-antiquark annihilation to gluons are discussed as possible tools to investigate the existence (and handedness) of excited electrons and quarks. Properties of these particles can also be explored in e^+e^- and ep colliders; production cross-sections and the impact of these particles on structure functions are derived.

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A natural prediction of composite models is the existence of excited quarks and leptons /1/. Naively these excitations would be expected to have rather large masses, typically in the range of the composite mass scale Λ . It has been argued repeatedly that Λ might well be in the TeV region - it is nevertheless not excluded that at least some of these excitations could have smaller masses. In such a case they could be produced at the CERN $p\bar{p}$ collider or at the FNAL Tevatron (in the near future). These speculations /2,3/ have been stimulated by events recently reported from the UA1 and UA2 experiments /4/.

In this brief note we shall explore some more phenomenological consequences of excited fermions. We first present the complete modification of the cross section for e^+e^- annihilation into two photons, resulting from the exchange of a virtual excited electron. Similarly, contributions from exchanging excited quarks will affect the cross sections and the angular distributions of two-jet final states with large invariant mass. These modifications are confronted to the standard results. Excited quarks and leptons of masses up to 150 GeV could well be observed in ep collisions at HERA ($\sqrt{s} = 300$ GeV), or even up to 400 GeV if ep collisions in the LEP tunnel with $\sqrt{s} \sim 2$ TeV are made feasible. The effects of excited fermions on the structure functions are markedly different for spin 1/2 and spin 3/2 excitations. Longitudinal beam polarization can be a useful tool to further explore the weak isospin of excited fermions since their handedness and isospin are closely related.

The coupling between excited spin 1/2 fermions, light fermions and the photon is uniquely fixed to be of the magnetic moment type. To avoid a conflict with the extremely accurate $(g-2)$ measurements of electrons and muons, excited leptons may couple to one helicity component of the light leptons only. The effective Lagrangian is thus

given by

$$\mathcal{L}_{em} = \frac{ef_Y}{2m_*} \bar{e}^* \sigma_{\mu\nu} F^{\mu\nu} e_L + \text{h.c.} \quad (1)$$

m_* denotes the mass of the excited electron e^* , f_Y is an arbitrary constant, presumably of order 1, and e_L is the left-handed component of the electron. (Alternatively, we could choose e_R . If not stated differently, our results are insensitive to this choice).

e^+e^- collisions can be a valuable source of information on excited leptons for $\sqrt{s}$ comparable but not necessarily above m_* . If $\sqrt{s} > m_*$, then the production of excited electrons or muons together with their ground state partners is possible /3,5/. Virtual contributions to $e^+e^- \rightarrow \gamma\gamma$ can be important already for $\sqrt{s}$ somewhat below m_* . The leading contribution $\sim f_Y^2 s^2/m_*^4$ has been calculated earlier /6/, the complete differential cross section for longitudinally polarized beams reads

$$\begin{aligned} s \frac{d\sigma_{LL}}{d\Omega} &= s \frac{d\sigma_{RR}}{d\Omega} = 0 \\ s \frac{d\sigma_{RL}}{d\Omega} &= 2\alpha^2 \frac{1+u^2}{1-u^2} \\ s \frac{d\sigma_{LR}}{d\Omega} &= \alpha^2 \left\{ 2 \frac{1+u^2}{1-u^2} + 4 \left(\frac{f_Y^2 s}{4m_*^2} \right) \left[\frac{(1-u)^2}{1-u+2m_*^2/s} + (u \rightarrow -u) \right] \right. \\ &\quad \left. + 4 \left(\frac{f_Y^2 s}{4m_*^2} \right)^2 \left[\frac{(1-u)^2(1-u^2)}{(1-u+2m_*^2/s)^2} + (u \rightarrow -u) \right] \right\} \end{aligned} \quad (2)$$

where $u = \cos\theta$ and R/L refer to right or left-handed electron and positron polarizations /x1/. Note that only one helicity combination is affected. Had we chosen a different isospin assignment of e^* - replacing e_L by e_R - right and left-handed beam polarizations would be reversed.

Assuming that excited quarks exist, they would manifest themselves in proton-(anti)proton collisions; they would not only appear as resonances in quark-gluon collisions /2,3/ but would also lead to modifications of cross sections and angular distributions in two-jet production (e.g. $q\bar{q} \rightarrow gg$ as shown in Fig. 1) once the invariant mass of the two-jet system is sufficiently high. Such additional virtual exchanges would affect the 2-jet cross sections for $qg \rightarrow qg$ and $gg \rightarrow q\bar{q}$ as well. To facilitate the discussion, we shall concentrate on 2-jet final states, originating from $q\bar{q}$ annihilation. Such configurations dominate if events with a sufficiently high invariant mass of the 2-jet system, $m_{jj}/\sqrt{s} \gtrsim 1$, are selected. The effective coupling of excited and light quarks to gluons is given by the obvious generalization of equ. (1)

$$\mathcal{L}_s = \frac{g_s f_s}{2m_*} \bar{q} * \sigma_{\mu\nu} \vec{G}^{\mu\nu} \frac{\vec{\lambda}}{2} q + \text{h.c.} \quad (3)$$

Based on the diagrams in Fig. 1 it is straightforward to calculate the cross section for $q\bar{q} \rightarrow gg$ ($u = \cos\theta$),

$$\begin{aligned} s \frac{d\sigma}{d\Omega} = & \frac{\alpha_s^2}{9} \left\{ \frac{16}{3} \frac{1+u^2}{1-u^2} - 3(1+u^2) \right. \\ & + \frac{1}{3} \left(\frac{f_s^2}{4m_*^2} \right) \left[\frac{(1-u)^2(7+9u)}{1-u+2m_*^2/s} + (u \rightarrow -u) \right] \\ & \left. + \frac{16}{3} \left(\frac{f_s^2}{4m_*^2} \right)^2 \left[\frac{(1-u)^2(1-u^2)}{(1-u+2m_*^2/s)^2} + (u \rightarrow -u) \right] \right\} \quad (4) \end{aligned}$$

The cross sections for $qg \rightarrow qg$ and $gg \rightarrow q\bar{q}$ then follow from crossing rules. The amplitude with q^* exchange does not exhibit the singularity at $t \approx 0$ for light quarks and, as a consequence, the additional contributions lead to more isotropic angular distributions. In Fig. 2a we therefore compare the differential distributions with and without

exchange of virtual excited quarks for different values of $\sqrt{s}/m_*$, f_s chosen to be 1. $\sqrt{s}$ denotes the mass of the 2-jet system and $\cos\theta$ the scattering angle in the 2-jet rest frame. A significant change can only be observed in the angular distribution for $m_*/\sqrt{s} \gtrsim 1.5$ but then the effect increases rapidly with increasing $\sqrt{s}$.

By choosing the 2-jet invariant mass sufficiently large, it is possible to separate quark-antiquark collisions from quark-gluon or gluon-gluon processes so that the above results are independent of parton luminosities. However, it seems difficult (if not impossible) to separate gluon from quark jets at present. If we add the $q\bar{q}$ scattering cross section, the effect of excited quark exchange turns out to be less pronounced, as shown in Fig. 2b. For $\sqrt{s}/m_* \approx 2$ it just becomes visible and only above this value it increases dramatically. Irregularities in high-energy jet production cross sections could therefore provide a first signal of additional excited quark contributions, just giving the hint to search for the more direct formation process $qg \rightarrow q^*$.

Were the masses of excited fermions indeed as low as 150 GeV, they might be produced at HERA or at a future ep collider in the LEP tunnel. Excited quarks would manifest themselves through dramatic scaling violations in the structure functions $/x^2/$. Furthermore, the final state topology would change considerably once excited quarks are produced. The energy, x and y dependence of these additional contributions would allow to discriminate between spin 1/2 and spin 3/2 excitations and thus yield valuable information on the underlying preon dynamics.

Defining the cross section and structure functions for deep inelastic scattering as usual through

$$\frac{d\sigma}{dx dy} = \frac{4\pi\alpha_s^2}{Q^4} \left[F_1 xy^2 + F_2(1-y) + F_3xy \left(1 - \frac{y}{2}\right) \right] \quad (5)$$

the contributions from excited quarks to the structure functions can be written as

$$\begin{aligned}\Delta F_1 &= \sum (V_q^2 + A_q^2) \frac{1}{2} (q + \bar{q}) n_1 \\ \Delta F_2 &= \sum (V_q^2 + A_q^2) \xi(q + \bar{q}) n_2 \\ \Delta F_3 &= \sum 2(V_q A_q) (q - \bar{q}) n_3\end{aligned}\tag{6}$$

where

$$\begin{aligned}V_q &= Q_e f_Y(q^*) + \frac{2I_3(e) - 4Q(e)\sin^2\theta_w}{\sin^2 2\theta_w} f_Z(q^*) \frac{Q^2}{Q^2 + m_Z^2} \\ A_q &= \frac{2I_3(e)}{\sin^2 2\theta_w} f_Z(q^*) \frac{Q^2}{Q^2 + m_Z^2}\end{aligned}\tag{7}$$

q and $\bar{q}$ denote the Q^2 evolved quark and antiquark distributions evaluated for the rescaled variable $\xi = x(1+m_*^2/Q^2)$. $f_Y(q^*)$ and $f_Z(q^*)$ are related to the $SU(2) \times U(1)$ couplings f and f' of excited quarks through

$$\begin{aligned}f_Y(q^*) &= f I_3(q^*) + f' Y(q^*)/2 \\ f_Z(q^*) &= f I_3(q^*) \cos^2\theta_w - f' \frac{1}{2} Y(q^*) \sin^2\theta_w\end{aligned}\tag{8}$$

For spin 1/2 the n_i are given by /*3/

$$\begin{aligned}n_1 &= n_3 = 1/2 \\ n_2 &= Q^2/2m_*^2\end{aligned}\tag{9}$$

Excited quarks with spin 3/2 may couple to light quarks and the electromagnetic field through one operator of dimension 5 and two

operators of dimension 6,

$$\begin{aligned}
 \mathcal{L}^1 &= ie \frac{f_Y^1}{m_*} \bar{f}_\alpha^* \gamma_\nu F_{\alpha\nu} f_L + \text{h.c.} \\
 \mathcal{L}^2 &= ie \frac{f_Y^2}{2m_*^2} \bar{f}_\alpha^* \sigma_{\mu\nu} \partial_\alpha F_{\mu\nu} f_L + \text{h.c.} \\
 \mathcal{L}^3 &= e \frac{f_Y^3}{2m_*^2} \bar{f}_\alpha^* \partial_\nu F_{\alpha\nu} f_L + \text{h.c.}
 \end{aligned} \tag{10}$$

Analogous expressions describe the general couplings to Z^0, W and to the gluon. $\mathcal{L}^3$ vanishes for real photons and gluons. The following discussion will be limited to $\mathcal{L}^1$ and $\mathcal{L}^2$. The contributions to the structure functions ensue from equ. (6) by substituting

$$\begin{aligned}
 n_1 &= \frac{1}{12} (Q^4/m_*^4 + 3) \quad ; \quad n_2 = \frac{Q^2/m_*^2}{12} (Q^2/m_*^2 + 3) \\
 n_3 &= \frac{1}{12} (Q^4/m_*^4 - 3)
 \end{aligned} \tag{11}$$

if the couplings are dominated by $\mathcal{L}^1$ and by substituting

$$\begin{aligned}
 n_1 &= n_3 = \frac{1}{12} \frac{Q^4}{m_*^4} x^{-1} (1 + m_*^2/Q^2) \\
 n_2 &= \frac{1}{12} \frac{Q^6}{m_*^6} x^{-1} (1 + m_*^2/Q^2)
 \end{aligned} \tag{12}$$

if $\mathcal{L}^2$ dominates.

In Fig. 3 we show the evolution /x4/ of the structure function F_2 for fixed values of x as predicted by the standard model (including neutral current effects) and their modification due to excited quarks of spin 1/2 and 3/2, assuming $f_Y = f_Z = 1$. Once Q^2 is above threshold

for q^* production [$Q^2 > m_*^2 x / (1-x)$], F_2 rises rapidly. In addition to their impact on the structure functions, q^* decays into $q+W$, Z , γ or gluon provide clean signatures for their detection through final state topologies. The total cross section for the production of q^* in ep collisions is presented in Fig. 4 as a function of s .

It is dominated by quasi-real photoproduction $\gamma + q \rightarrow q^*$ and follows from folding the photoproduction cross section with the Weizsäcker-Williams photon spectrum,

$$\sigma(ep \rightarrow q^*) = 4\pi^2 (2s_{q^*} + 1) \sum_q \frac{\Gamma(q^* \rightarrow q\gamma)}{m_*^3} \tau \frac{\partial \mathcal{L}^{\gamma q}}{\partial \tau} \quad (13)$$

$$\Gamma(q^* \rightarrow q\gamma) = \alpha f_Y^2 \frac{m_*}{4} \left[1; \frac{1}{4}; \frac{1}{12} \right] \quad (14)$$

The numbers in the bracket refer to excited spin 1/2 and 3/2, ¹ and ² coupling, respectively. $\partial \mathcal{L}^{\gamma q} / \partial \tau$ is the photon-quark luminosity for $\tau = m_*^2/s$ in electron-proton collisions; a convolution of the Weizsäcker-Williams spectrum with the quark-parton density,

$$\frac{\partial \mathcal{L}^{\gamma q}}{\partial \tau} = \int_{\tau}^1 \frac{dx}{x} \gamma(x) q(\tau/x) \quad (15)$$

$$\gamma(x) = \frac{\alpha}{2\pi} \log \left(\frac{m_*^2}{4m_e^2} \right) \frac{1 + (1-x)^2}{x} \quad (16)$$

From the same approximations we predict also a sizeable cross section for e^* production /*6/

$$R(e^{+*} + e^{-}) + c.c. = \frac{3}{4} (2s+1) f_Y^2 \log \left(\frac{s}{4m_e^2} \right) \frac{s}{m_*^2} \left| 1 + (1-m_*^2/s)^2 \right| \quad (17)$$

which allows to produce excited electrons nearly up to the kinematical limit with sizeable cross section.

Production of excited leptons and their decays into $e\gamma$, eZ or νW (if kinematically allowed) should lead to even more spectacular events. The differential cross sections for these reactions /*5/ are obtained by substituting $\xi \rightarrow x$ and $y \rightarrow y (1 + m_*^2/Q^2)$ on the right-hand side of equs. (5), (6), (11) and (12), and exchanging q with e in the definitions of V and A (equ. (7)). Note that in both bases the sign of F_3 would be reversed if the handedness of the coupling of the excited fermions was altered. The total e^* production cross section can easily be derived from the q^* cross section by substituting m_q for m_e , and multiplying the result with $\langle e_q^2 \rangle$ for the various excited quark species.

Other reactions might be observed in ep collisions if excited neutrinos exist. The analysis presented above can easily be repeated for the weak interaction process $e \rightarrow \nu^*$, ν^* subsequently decaying to $\nu\gamma$, νZ or eW . As one neutrino always escapes, such reactions will be a little more difficult to discover experimentally.

One may also conceive of q^* production through a contact term, e.g. through

$$A = 1/\Lambda^2 \bar{e}_L \gamma_\mu e_L \bar{q}^* \gamma^\mu q_L .$$

The subprocess cross section $\left[\hat{\sigma} = \frac{1}{16\pi} \frac{\hat{s}}{\Lambda^4} \left(1 - \frac{m_*^2}{s} \right)^2 \right]$ together with

$\Lambda = 1 \text{ TeV}$ then leads to a production rate at least one order of magnitude smaller than the one estimated above.

Longitudinally polarized electron beams can offer substantial advantages in the study of excited fermions. It has been noted earlier that the handedness of the couplings and weak isospin assignments of the excited particles are closely related. It is apparent from equ. (1) that only electrons of one helicity (for $I = 1/2, 3/2$ the left-handed, for $I = 0, 1$ the right-handed ones) are able to produce excited electrons. Together with the observation or absence of the

$e^* \rightarrow \nu W$ decay mode (which requires $I(e^*) = 1/2$ or $3/2$) the isospin assignment is uniquely fixed. The weak isospin of excited quarks can be explored in a similar manner. For polarized beams the impact of F_3 will be maximally enhanced compared to F_1 and F_2 . The sign of F_3 will be directly correlated to the handedness of the q^* couplings and thus to their weak isospin.

Since we have considered coupling (1) for on and off shell photons or excited fermions, one will in general expect form factor effects. However, it might well be that these are governed by a scale Λ somewhat higher than the mass of the lightest excited fermion. Furthermore we have kept Q^2 in the energy range of m_*^2 and therefore ignore form factor effects in this analysis. As far, as effects on the structure function are concerned, they would simply appear as multiplicative factors. The production cross section in ep and e^+e^- collisions is practically unaffected.

To summarize. Polarized beams in e^+e^- annihilation to two photons can give important information on existence and handedness of excited electrons. Contributions from the exchange of excited quarks to the QCD process $q\bar{q} \rightarrow gg$ will substantially affect the angular distribution once $\sqrt{s} \gtrsim m_*$. This effect is partly diluted if elastic $q\bar{q}$ scattering is superimposed. Production of excited quarks and electrons at HERA or at a future ep collider with $\sqrt{s} \sim 2$ TeV should be possible for masses up to 150 GeV and 400 GeV, respectively, provided the unknown coupling constants f_Y and f_Z are of order 1. Spin 1/2 and 3/2 excitations will lead to quite different Q^2 , x and y dependences of the cross sections. Longitudinally polarized beams could help again to disentangle the weak isospin of excited fermions.

FOOTNOTES

/x1/ The complete spin-averaged cross section has also been obtained by G. Pancheri and Y. Srivastava, unpublished.

/x2/ For a general discussion, see Ref. /7/.

/x3/ These results disagree with those of Ref. /5/. We thank F. Renard for correspondence.

/x4/ Parametrizations of quark distributions are adopted from Ref. /8/.

/x5/ These cross sections have also been discussed in Ref. /9/.

/x6/ Production of the other excited fermions in e^+e^- collisions is already discussed in refs. 3,5.

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FIGURE CAPTIONS

- Fig. 1 Feynman diagrams of the process $q\bar{q} \rightarrow gg$ including excited quark exchange.
- Fig. 2 Angular distribution (a) of gluon-jet final states in quark-antiquark collisions, and (b) of gluon and quark-jet final states, including excited quark exchange in both cases.
- Fig. 3 Q^2 dependence of the proton structure function F_2 if excited quarks with mass $m_* = 150$ GeV and spin $1/2$ or $3/2$ are produced.
- Fig. 4 Total cross section for excited quark and excited electron production in ep collisions, calculated in the Weizsäcker-Williams approximation for quasi-real photons. Spin $3/2$ cross sections may be obtained by applying the scale factors noted in the text and those for excited electrons by multiplication with $\approx 1/6$.

Fig. 1

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4