ARE THERE HEAVY QUARKS OF MASS 23 GeV?

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An excess of events with an isolated muon and low thrust observed by the MARK-J collaboration at the highest PETRA energy $\sqrt{s} = 46.7$ GeV, is found to be consistent with the near threshold production of heavy quarks of charge $-1/3$. A natural candidate is a fourth-generation “down” quark or, possibly, a member of a 27 representation of $E_6$. Signatures of such heavy quark pair production at the CERN $p\bar{p}$ collider are investigated and it is concluded that the present data have a chance to confirm the signal.

Recently the MARK-J collaboration have reported [1] events with isolated muons and a broad energy flow at the highest accessible energy ($46.30 \text{ GeV} < \sqrt{s} < 46.78 \text{ GeV}$) of $e^+e^-$ collisions at PETRA. They observed eight events with low thrust [2] values ($T < 0.8$) and a muon, whereas at most 19 events are expected from an extrapolation of their lower-energy data taken at $36.9 \text{ GeV} < \sqrt{s} < 46.3 \text{ GeV}$. None of the other experiments at PETRA have been able to confirm or to reject these events\textsuperscript{1}, and with the recent modifications PETRA is no longer able to reach 46 GeV. Our main purpose is to examine whether the CERN $p\bar{p}$ collider data can confirm or eliminate possible interpretations of these events.

The main features of the eight MARK-J events are [1] (1) the muons have low momentum (in the range 2 to 5 GeV) with the exception of one very energetic muon of 16 to 5 GeV, (2) one event has two muons (of 4.5 and 2.2 GeV), (3) eight of the nine observed muons are well isolated, satisfying $|\cos \delta| < 0.7$, where $\delta$ is the opening angle between the muon momentum and the thrust axis (whereas for $T < 0.8$, $|\cos \delta| < 0.7$ only 0.5 muons are predicted from the lower energy data), (4) the missing energy is about 10% to at most 20% of the total energy.

Events with broad energy flow and isolated muons suggest heavy quark pair production. Suppose we assume a top-quark mass of 23 GeV so that the open top threshold lies in the highest-energy bin, then we expect then $3S_1$ toponium states ($n = 1, 2, \ldots$) at lower energies. To calculate the $nS_1 \to e^+e^-$ decay widths, $\Gamma_{ee}(nS)$, we use the QCD-motivated potential of ref. [4], which reproduces the observed $c\bar{c}$ and $b\bar{b}$ data including the leptonic widths. We find

$$M(1S) = 45.1 \pm 0.3 \text{ GeV},$$
$$\Gamma_{ee}(1S) = 3.3 \pm 0.8 \text{ keV},$$
$$M(2S) - M(1S) = 0.59 \pm 0.05 \text{ GeV},$$
$$\Gamma_{ee}(2S) = 1.5 \pm 0.2 \text{ keV},$$
$$M(3S) - M(1S) = 0.92 \pm 0.05 \text{ GeV},$$
$$\Gamma_{ee}(3S) = 0.9 \pm 0.1 \text{ keV}.$$  \hspace{1cm} (1)

where the errors correspond to the uncertainty in the short-distance potential arising from changing the QCD mass scale, $\Lambda_{MS}$, from 0.1 to 0.4 GeV. The comparison of (1) with the 95% confidence limit [3,1]

$$\Gamma(\theta \to e^+e^-) \cdot B(\theta \to \text{hadrons}) < 1.9 \text{ keV}$$

for $\sqrt{s} < 46.78 \text{ GeV}$ \hspace{1cm} (2)

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\textsuperscript{41} For a recent review see e.g. ref. [3]
for a new resonance produced at PETRA, makes the presence of a top quark of mass 23 GeV rather unlikely.

Another possibility is that the MARK-J events could be due to L\bar{L} production, where L is a fourth-generation charged lepton (of mass 23 GeV) with decay branching fractions

\[ B(L \rightarrow \nu_L \bar{\nu}_L) \approx 0.11, \]
\[ B(L \rightarrow \nu_L \bar{e}) \approx B(L \rightarrow \nu_L \bar{d}) \approx 0.33 \]  

Detailed decay calculations [5] show that L\bar{L} events with primary decay muons (L \rightarrow \mu) have on average 50\% missing energy and muon momentum of about 8 GeV. Events with secondary muons (L \rightarrow c \rightarrow \mu and L \rightarrow \tau \rightarrow \mu) occur at 3B(c \rightarrow \mu) + B(\tau \rightarrow \mu) \approx 0.5 times the primary muon rate and have about 40\% missing energy and average muon momentum of about 3 GeV. The observed missing energy is much smaller than that for L\bar{L} events, and this alone excludes a sequential heavy lepton as an explanation of the MARK-J events.

Now the experimental bound, eq (2), does not rule out bound states of a charge –1/3 heavy quark. Possible candidates are either a fourth-generation weak-isospin down quark (which we call \( v \) quark [6]) or a weak singlet, colour triplet quark (the h quark), which together with h and a family of 15 known fermions, belongs to the 27 representation of the \( E_6 \) gauge group. The latter possibility has recently received great attention due to the advent of anomaly-free super-string theories [8] (the first serious candidates for the theory of quantum gravity) which predict \( E_6 \) as the most promising grand unification group.

Assuming a continuation of the observed trend of smaller mixing between generations as the generation number increases, then the \( v \) quark dominantly decays into a charmed quark and a virtual W boson. Thus the branching fractions are predicted to be

\[ B(v \rightarrow c \ell \bar{\nu}_\ell) \approx 0.11, \]
\[ B(v \rightarrow c \bar{\nu}) \approx B(v \rightarrow c \bar{e}) \approx 0.33, \]  

with \( \ell = e, \mu, \tau \). On the other hand the h quark, being an SU(2)_L singlet, can only decay through mixing with the d quark. To maintain weak universality the mixing must be small, giving [9]

\[ B(h \rightarrow \text{hadrons}) \approx 0.66, \quad B(h \rightarrow u \ell \bar{\nu}_\ell) \approx 0.08, \quad B(h \rightarrow d \ell \bar{\nu}_\ell) \approx 0.02, \quad B(h \rightarrow d \bar{\nu}) \approx 0.01 \]

Note that the \( v\bar{v} \) and hh production cross sections are equal for quarks of the same mass up to small Z-boson contributions at PETRA energies, and that \( B(v \rightarrow c \ell \bar{\nu}_\ell) \approx B(h \rightarrow u \ell \bar{\nu}_\ell) \). If the h quark has a larger mixing to the s or b quark than to the d quark, then h \( \rightarrow c \ell \bar{\nu}_\ell \) and the muon spectrum (including secondary as well as primary decays) arising from hh and vv production would be very similar. Therefore most of the discussion presented below for the v quark applies equally well to the h quark.

For vv events, the muons arising from secondary decays (v \( \rightarrow c \rightarrow \mu \) and v \( \rightarrow \tau \rightarrow \mu \)) occur at 1.2B(c \( \rightarrow \mu \)) + B(\tau \rightarrow \mu) \approx 1.6 times the rate of events with primary decay muons (v \( \rightarrow \mu \)). Moreover, the missing energy is small, being on average about 15\% for events with a primary muon and much less for those containing a secondary muon. The muon-momentum distributions arising from primary and secondary decays of V mesons are shown in fig. 1 for e^+e^- \rightarrow v\bar{v} at \( \sqrt{s} = 46.6 \) GeV with \( m_v = 23 \) GeV. The curves are obtained using the \( V - A \) matrix elements for v decays, the charm quark fragmentation function of ref. [10] with \( e = 0.2 \), and the collinear approximation for the secondary decays, which although not strictly valid

\[ \text{Fig 1 Muon-momentum distributions for } e^+e^- \rightarrow v\bar{v} \text{ at } \sqrt{s} = 46.6 \text{ GeV arising from primary decays (v \rightarrow \mu) and from secondary decays (v \rightarrow c \rightarrow \mu \text{ and } v \rightarrow \tau \rightarrow \mu) with } m_v = 23 \text{ GeV.} \]

The arrows indicate the momenta of the nine muons observed by the MARK-J collaboration [1], the detection efficiency depends on the muon momentum and, in fact, muons below 1.5 GeV cannot be detected (shaded region) [1].
for low-momentum muons should give a reasonable guide to the distribution. No acceptance corrections have been made. The momenta of the observed muons are indicated by arrows at the top of fig. 1, and have large experimental uncertainties. The three highest-momentum muons can be seen in the cos θ − φ "Lego" plot [1] to be relatively more isolated from hadronic activity and may be attributed to primary muons. Approximately half of the ν̄ν events are expected to contain muons and the eight observed events correspond to a ν̄ν production cross section of about 0.15 m units of σ(e+e− → γ* → μ+μ−), which is consistent with the expectations of a charge −1/3 quark in the resonance region.

Since the isolated muon events observed by the MARK-J collaboration appear consistent with the production and decay of charge −1/3 quarks, it is important to study ν̄ν production at the CERN p̄p collider. The production cross section due to QCD fusion subprocesses (q̄q → ν̄ν and gg → ν̄ν) is about 6.1 nb at √s = 630 GeV using the parton distributions of Duke and Owens (set I) [11], and that via an intermediate Z boson (Z → ν̄ν) is predicted to be 0.16 nb. The best signatures of these events are the isolated electrons or muons from the semileptonic decays ν → eν̄μν̄. Primary-decay leptons from heavy quarks have a much better chance of being well isolated from accompanying hadronic debris than the leptons from b or c decays. We calculate the primary-decay lepton and accompanying jet distributions assuming that the ν quarks fragment into unpolarized (V) mesons, using a heavy quark (Q) fragmentation function of the form of ref. [10] with eQ = 0.5/mQ2 in units of GeV, and that the V and ν̄ mesons then decay with bare W − A matrix elements. The momenta of the final decay products contribute to jet formation. We impose acceptance cuts in order to approximately simulate the UA1 lepton-isolation and jet-acceptance criteria used in their top-quark search [12 13]. Namely, for the electron + jets events we require (i) that the electron transverse momentum pT > 15 GeV, (ii) that the transverse energy deposited in a cone around the electron track given by ∆R = [(∆φ)2 + (∆η)2]1/2 < 0.7 should be less than 10% of the electron energy, (iii) that the transverse energy in a similar cone with ∆R < 0.4 be less than 1 GeV, (iv) that hadronic energies (final decay momenta) be combined if two adjacent momenta satisfy ∆R < 1, and (v) that hadronic energies be accepted as jets if their transverse momenta pT(jet) > 10 GeV and rapidity |η(jet)| < 2.5. For mass 23 GeV quarks we expect the (electron + n jet) contributions to be sensitive to the efficiency of identifying low-pT jets, and to examine this effect we repeated the calculations using pT(jet) > 8 GeV.

We show in table 1 the cross sections calculated, using the above criteria, for events containing a single isolated electron plus n jets arising from the decay of ν quarks (of mass 23 GeV) and from the decay of t quarks (of mass 40 GeV) produced in p̄p collisions at √s = 630 GeV. Contributions to ν production via a W boson, and Z → t̄t̄, are small and are not shown. There are several sources of uncertainty in these predictions coming from possible effects of parton-fragmentation and of spectator-jet contributions, from higher-order QCD effects, and from the choice of structure functions and of aQ. Nevertheless the results.

### Table 1

The lepton plus n-jet cross sections (in pb) for ν quark (23 GeV) and t quark (40 GeV) production in p̄p collisions at √s = 630 GeV using the lepton-isolation and jet-acceptance criteria described in the text. The cross sections correspond to pT(jet) > 10 GeV, with those for pT(jet) > 8 GeV in parentheses. The cross sections for W and Z initiated events are normalized to σ(W* + W̄) = 5.3 nb and σ(Z) = 1.6 nb [14].

<table>
<thead>
<tr>
<th>Subprocesses</th>
<th>σ(e + n jets) pb</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>n = 0</td>
</tr>
<tr>
<td>(gg, q̄q) → ν̄ν</td>
<td>18 (0.6)</td>
</tr>
<tr>
<td>Z → ν̄ν</td>
<td>–</td>
</tr>
<tr>
<td>(gg, q̄q) → t̄t̄</td>
<td>0.1 –</td>
</tr>
<tr>
<td>W → (t̄b, t̄b)</td>
<td>0.5 (0.3)</td>
</tr>
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</table>

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Mass distributions of $e^+d$jet events

Fig. 2 Invariant-mass distributions for electron + dijet events resulting from heavy-quark production in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV. The continuous curves are the distributions from the sum over the subprocesses $q\bar{q}$, $gg$, $Z \rightarrow v\bar{v}$ with $m_v = 23$ GeV, whereas the dashed curves result from $q\bar{q}$, $gg \rightarrow t\bar{t}$ and $W \rightarrow t\bar{b}$, $\bar{t}b$ with $m_t = 40$ GeV. The electron-isolation and jet-acceptance criteria are applied as described in the text (jet $p_T >$ GeV) should give a semiquantitative guide to the expected signal.

We note from Table 1 that the lepton + dijet signal, used to identify the $t$ quark, is populated approximately equally by events coming from $v\bar{v}$, and top-quark production, moreover, we find the background from $b\bar{b}$ and $b\bar{b}X$ events is negligible. Fig. 2 shows the $M(e_j1\nu_T)$ and $M(e_j2\nu_T)$ invariant-mass distributions for the electron + dijet events. Here $\nu_T$ indicates the neutrino four momentum with the (unknown) component along the beam direction set to zero, and $j_2$ corresponds to the jet with the lower $p_T$, so that for the majority of events we would expect $M(e_j2\nu_T)$ to average to the mass of the heavy quark parent. The double peak in $M(e_j1\nu_T)$ shows that this is only partially true for the $v\bar{v}$ events, using the above acceptance cuts, many events have both $j_1$ and $j_2$ coming from one $v$-quark decay and the electron from the other.

The $v$- and $t$-quark signals look quite different (cf. Fig. 2) in our parton-model calculation, which assumes the momentum of the electron and jets can be perfectly measured. In practice the distributions will be much less sharp, and less distinctive, due to various effects which we have ignored, such as jet-fragmentation and spectator-jet contributions, as well as the experimental uncertainties in resolving jets and measuring their momenta.

Despite the large cross section of 6.7 nb for $v\bar{v}$ production as compared to 1.1 nb for $t$ production, we see the $v$-quark signal is weaker. The electron and jets from $v$ decays have, on average, lower $p_T$ and are much more often eliminated by (and sensitive to) the acceptance criteria, than those from $t$ decays. In view of the sensitivity of the $v\bar{v}$ signal to the detection efficiencies, and to the hadron dynamics, it is not clear if the available electron + dijet data from the $p\bar{p}$ collider can exclude quarks of mass around 23 GeV.

Apart from the small difference in the semileptonic branching fractions (cf. eqs (4) and (5)) and the $Z$-initiated contribution (which is negligible anyway), the signature for $hh$ production should be comparable to that for $v\bar{v}$ production. Events containing two isolated leptons are additional signatures for these quarks. Although significant mixing in the neutral-$V$-meson system is not expected in any of the extrapolations of the KM matrix elements considered in Ref. 6, large mixing is expected among neutral mesons containing an $h$ quark, that is in both the $(h\bar{d})-(l\bar{s})d$ and $(h\bar{s})-(l\bar{d})$ systems, due to its direct neutral-current couplings. This may lead to observable signals, such as relatively isolated like-sign dimuons at hadron colliders. The $h$ can be clearly distinguished from the $v$ quark by its small coupling to the $Z$ and the resulting lack of forward-backward asymmetry in $e^+e^-$ annihilation experiments at TRISTAN energies.

Note that the muon-momentum distribution of the MARK-J events suggests more muons arise from secondary than from primary decays (see Fig. 1) and so the $h$ quark would have to have larger mixing to the $s$ or $b$ quark such that $h \rightarrow c\bar{X}$ dominates over the $h \rightarrow u\bar{X}$ decays.

In summary, we find that the MARK-J isolated muon events at the top PETRA energy can be interpreted in terms of a charge $-1/2$, mass 23 GeV quark. A natural candidate is a fourth-generation "down" quark (denoted by $v$) or, possibly, a $h$ quark belong-
ing to the 27 representation of $E_6$. We noted that $h\bar{h}$ and $\nu\bar{\nu}$ phenomenology could be very similar. Since PETRA can no longer reach this energy, the confirmation of the isolated muon signal must await $e^+e^-$ collisions at TRISTAN or SLC/LEP. However, dedicated studies at the CERN $p\bar{p}$ collider should be able to identify a $\nu$ (or $h$) quark of this mass. We presented rates for isolated lepton + $n$ jet events arising from $\nu\bar{\nu}$ (or $h\bar{h}$) production and compared these with those coming from $t\bar{t}$ and $b\bar{b}$ production. Provided there is good identification of jets with $p_T \simeq 10$ GeV, the present $p\bar{p}$ data should be able to decide if such a quark exists.

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References