SEARCH FOR STABLE EXCITED QUARKS

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A major puzzle in the standard model is the existence of three (or more) generations of quarks and leptons. A popular speculation is that quarks and leptons are not fundamental but rather are bound states of some new types of constituents. Excited quarks in non-standard representations of color SU(3) arise naturally in many such models. In this note we consider the possibility of quarks in triality-zero color representations, e.g. 8 or 10.

The lightest hadron containing a triality zero quark q^* is likely to be essentially stable. Conservation of color and of angular momentum forces the q^* to decay into three ordinary quarks q (or three antiquarks) plus an arbitrary number of gluons and $q\bar{q}$ pairs. Thus if the q^* has fractional charge, it must be absolutely stable provided only that charge and color are conserved. If it has integral charge, then in principle it can decay, e.g. by $q^* \rightarrow q + q + q$.

However, in the context of SU(3) x SU(2) x U(1) gauge theories, the only allowed renormalizable interactions are

$$\bar{q}^* \not{G} q^* , \ \bar{q}^* \not{W} q^* , \text{ and } \bar{q}^* H q^*$$

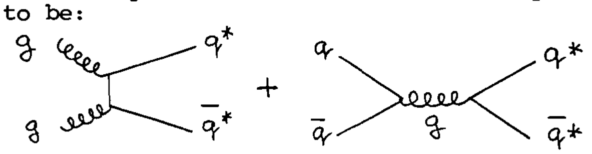
where G is the gluon, W is any of γ, $W^{\pm}$, Z^{o}, and H is any color singlet Higgs field. All of these interactions conserve q^* number, so within the standard model the lightest q^* must be stable. It can decay only through some new interaction, presumably a spontaneously broken gauge theory with a mass scale $M >> m_W$. If the coupling constant of this new interaction is q, then the q^* decay rate is

$$\Gamma \sim \frac{q^4}{M^4} m_q^5 ,$$

which is small for large M.

Provided that color is confined, the q^* must form color singlet hadrons with ordinary quarks and gluons. Any triality zero combination of quarks and gluons has integral charge so a fractionally charged q^* gives fractionally charged hadrons, and an integrally charged q^* gives integrally charged hadrons.

The purpose of this note is to describe a method for identifying such stable excited quarks via their time of flight. If these states are heavier than 50 GeV or so then it is only at hadron-hadron colliders that they could be produced in the near future. The dominant production mechanisms are expected to be:



These diagrams have been calculated by J. Leveille at the summer study, and integrated using ISAJET[1] for a q^*_{10} , a quark in the 10 representation. The resulting cross sections for a $\sqrt{s}$ = 800 GeV pp collider and a $\sqrt{s}$ = 2 TeV $\bar{p}p$ collider are shown in Fig. 1. The rates for producing q^*_{10} pairs in a 10^7 sec run at these colliders, assuming luminosities of 10^{33} $cm^{-2}sec^{-1}$ and 10^{30} cm^{-2} sec^{-1}, respectively, are shown in Fig. 2. We expect a total yield of thousands of events with q^*_{10} masses up to 200 GeV/c^2 .

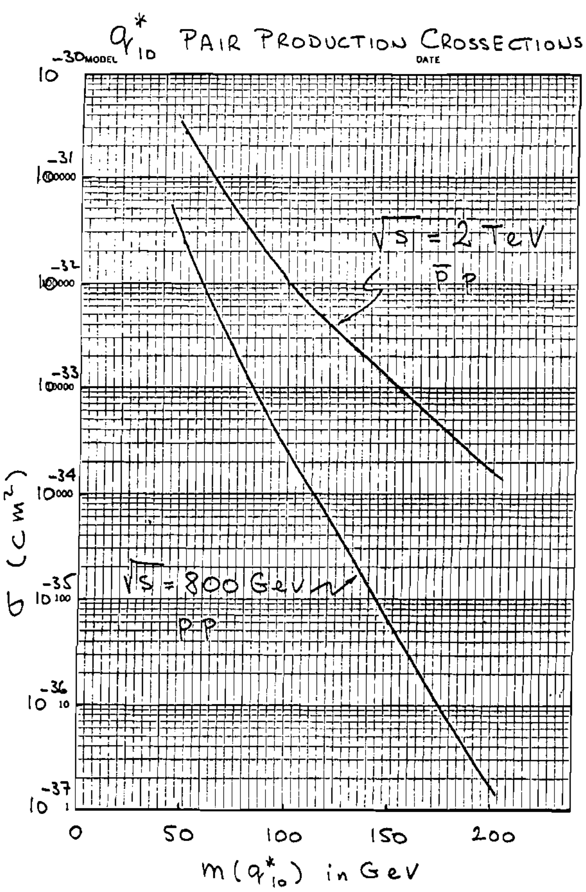


Fig. 1

We expect that the mechanism of color confinement in QCD will cause a jet of hadrons to form from the q^*. Rather general arguments[2] suggest that the heavy stable hadron containing the q^* should carry most of the momentum of the jet. This has been verified experimentally for D mesons from c quarks.[3] In our calculations, we have made the simplifying assumption that the q^* hadron carries all of the jet momentum. However, one should remember in designing an experiment that if the q^* is really stable, it will deposit only its kinematic energy in the calorimeter. Even a fairly small fraction of the jet momentum carried by ordinary hadrons could be significant compared to this kinetic energy, so the q^* hadron may not appear isolated.

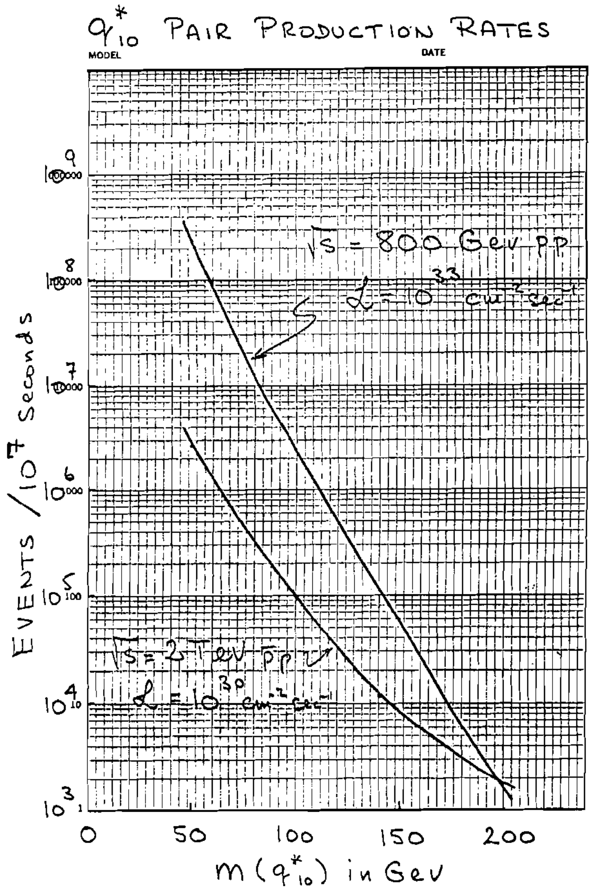


Fig. 2

In what follows, we assume that the charge of the stable q^* hadron is ± 1. If the charge is 1/3, the time-of-flight technique described here is liable to be somewhat compromised, although it probably can be made to work. However measuring dE/dx would give us a very effective extra handle on identifying the q^*. As the techniques involved are the same as those employed in free quark searches, we will not discuss them further. If these particles were very heavy, i.e. in the 50 to 200 GeV mass range, then a large fraction of them would have a small enough p to be identified by time-of-flight techniques.

We consider here the possibility of adapting general purpose large solid angle detector for this search. A hadron calorimeter would be used to measure the kinetic energy of each of the q^*'s, and a central drift chamber system in a magnetic field would define its trajectory and measure its momentum. Time-of-flight scintillation counters would be inserted just inside and just outside of the drift chambers, as shown in Fig. 3. If the TOF layers are separated by a flight path of 1.0 meters, then a $\beta = 1$ background particle will take 3.3 nsec to traverse the gap. We assume that the time of flight can be measured to $\sigma = 250$ picosec. Requiring a 5σ separation from the prompt peak implies that we can identify any particle with a time of flight longer than 4.55 nsec, i.e. with $\beta \leq 0.73$. This corresponds to a mass dependent upper limit on the momenta to which we are sensitive:

$$P_{max} = M/\sqrt{1/\beta_{max}^2 - 1} \ .$$

As an example, for a particle with a mass of 50 GeV/c^2, $P \leq 53$ GeV/c. These upper limits to the range of momenta to which the experiment will be sensitive are shown in the last column of Table 1.

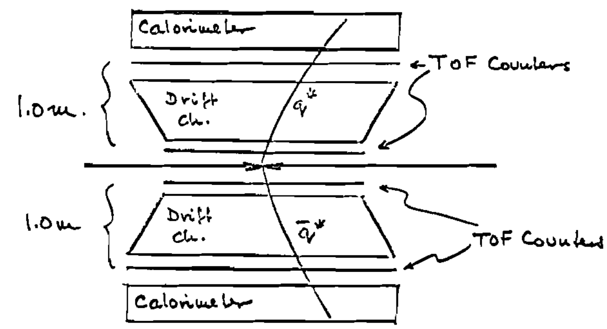


Fig. 3

The minimum momenta to which such a search would be sensitive is set by triggering and background considerations. The trigger we envision for these high P_t q^* pairs is to require a transverse energy $E_T = E \sin\theta$ larger than some minimum in each of two single calorimeter cells which are roughly back to back in azimuth. The background for such a trigger comes from ordinary high P_t jet events in which each jet deposits a lot of energy in a single cell ($\Delta y = 0.1$, $\Delta\phi = 9^o$). Using ISAJET, we find that at $\sqrt{s} = 800$ GeV and $\mathcal{L} = 10^{33}$ cm^{-2} sec^{-1} the rate for such events with $E_T > 15$ GeV is less than 100/sec. Having required two cells with $E_T > 15$ GeV as a pretrigger, we would then examine the drift chamber for two high-momentum tracks pointing at the appropriate cells. This would presumably allow us to reduce the trigger rate almost to the rate for two single particles each with $E_T > 15$ GeV, namely about 3/sec.

A minimum kinetic energy of 15 GeV corresponds to a minimum of 42 GeV/c for a 50 GeV/c^2 particle. The lower limits of the momentum range for this search as a function of mass are given in Table 1.

To keep the time-of-flight counters down to a reasonable size and to maximize the signal to background ratio we restrict the q^* pairs to within $\pm 45^o$ of 90^o. Thus candidates for q^* pairs would be required to contain a pair of single tracks in the drift chambers, both with $|y|<1$ and with P_t in the range shown in Table 1. The fraction of the total q^* pairs produced that satisfy these criteria have been calculated using ISAJET and are given in the columns labeled "Acceptance" in Table II. These acceptances range from 0.09 to 0.42. The total numbers of q^* pairs produced in 10^7 sec (see Fig. 2) are also given in Table 2. Finally, the number of q^* pairs that pass the acceptance criteria are shown in the columns labeled "Events Observed" in Table 2. There is sufficient sensitivity to see these excited quarks up to masses of 200 GeV/c^2.

The raw background of high P_t hadron pairs in the range shown in Table 1 is rather small. Calculations using ISAJET indicate that there will be a few x 10^3 pairs with both tracks having $P_t \geq 42$ GeV/c, and only a few x 10^2 with $P_t \geq 79$ GeV/c. The time of flight should then allow a clear separation between this background with $\beta \approx 1$ and the q^* signal with $\beta \leq 0.73$. Since the q^*'s must be produced in pairs, we can require $\beta \leq 0.73$ for both tracks, reducing the background to a negligible level.

Table 1: Range of P_t acceptance for q^*_{10} search near 90^o ($y = 0 \pm 1$)

$M(q^*_{10})$ GeV	$P_{t\,min}$ GeV/c	$P_{t\,max}$ GeV/c
50	42	53
100	57	105
150	69	158
200	79	213

It is important to note that a relatively good determination of the mass of the q^*_{10} can be made in spite of the rather poor momentum resolution of such an apparatus at high p. Assuming,

$$\frac{\sigma_p}{p} = 0.004\ p\ (\text{GeV})\ ,$$

and using the momentum on time of flight information, we find that in our worst case,

$$m \approx p \approx 200\ \text{GeV},\quad \sigma_m/m \approx 0.8\ .$$

For 500 events, considering that we have two chances to measure each event, the determination of m will be good to $0.8\ m/\sqrt{1000} \simeq 5$ GeV/c^2.

We thus believe that the search described here would be sensitive to stable decouplet quarks with masses up to 200 GeV or so. Of course, the search would also be sensitive to any other kind of charged, massive, stable particle, as long as the production cross section is comparable to those in Fig. 1. The main experimental challenge is to make the time of flight counters attain a reasonably good time resolution in the high rate environment implied by the luminosities envisioned here.

References

1. F.E. Paige, S.D. Protopopescu, "ISAJET": A Monte Carlo Event Generator for pp and $\bar{p}$p Interactions". These proceedings.
2. M. Suzuki, Phys. Lett. 71B, 139 (1977).
3. J.M. Yelton et al, Phys. Rev. Lett. 49, 430 (1982).
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Table 2: Event rates and acceptances for q^*_{10} search using $\mathcal{L} = 10^{33}\text{cm}^{-2}\text{sec}^{-1}$ for $\sqrt{s} = 800$ GeV collider; $\mathcal{L} = 10^{30}\text{cm}^{-2}\text{sec}^{-1}$ for $\sqrt{s} = 2$ TeV collider; 10^7 seconds data taking time .

$M(q^*_{10})$	$\sqrt{s} = 800$ GeV pp Collider			$\sqrt{s} = 2$ TeV $\bar{p}$p Collider		
GeV	Total Events	Acceptance	Events Observed	Total Events	Acceptance	Events Observed
50	$2.3\text{x}10^8$	0.09	$2\text{x}10^7$	$3\text{x}10^6$	0.09	$2.5\text{x}10^5$
100	$2.3\text{x}10^6$	0.26	$6\text{x}10^5$	$1\text{x}10^5$	0.20	$2\text{x}10^4$
150	$6.0\text{x}10^5$	0.42	$2.5\text{x}10^4$	$1\text{x}10^4$	0.28	$3\text{x}10^3$
200	$1.6\text{x}10^3$	0.34	$5\text{x}10^2$	$2\text{x}10^3$	0.26	$5\text{x}10^2$