HUNTING HALF-INTEGER CHARGED, HEAVY HADRONS FROM HIGHER DIMENSIONS

G INGELMAN and C WETTERICH

Deutsches Electronen-Synchrotron DESY, D-2000 Hamburg, Fed Rep Germany

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The phenomenology of stable half-integer charged hadrons predicted by certain higher dimensional unification models is examined Production cross sections and signatures for their detection in $p\bar{p}$ collider experiments are discussed in some detail

Certain compactifications of higher dimensional theories lead to exotic quarks with electric charge $+\frac{1}{6}$ and $-\frac{5}{6}$ in addition to a number of standard fermion generations [1]. Together with standard quarks they would form baryons and mesons with half-integer electric charge. Due to charge conservation, the lightest such hadron would be stable. Four-dimensional unification within SU(5), SO(10) or E_6 leads to a colour triality rule stating that all colour singlets must have integer electric charge. In contrast, higher dimensions allow for unification in groups with only real or pseudoreal representations like E_8 or SO(12). In this case, a generalized triality can allow for half-integer charged colourless states. Superstrings based on $E_8 \times E_8$ or SO(32) belong to this class of theories [2]. Generalized triality allows quarks with electric charge $Q = (3n + 1)/6$.

For this type of higher dimensional theories the appearance of exotic quarks in the four-dimensional low-energy spectrum depends on spontaneous compactification – on the embedding of $SU(3) \times SU(2) \times U(1)$ and the associated chirality index [3]. Indeed, examples have been found [1] leading to quarks in colour triplets with electric charge $+\frac{1}{6}$ and $-\frac{5}{6}$ in addition to several generations of standard quarks with charge $+\frac{2}{3}$, $-\frac{1}{3}$. There are also antiquarks with opposite charges. Depending on the sign of the index, the left-handed exotic quarks belong to weak doublets and left-handed antiquarks are weak singlets or vice versa (antiquarks form doublets and quarks are singlets). The exotic quarks form, together with some standard fermions, anomaly-free exotic generations [1]. Chirality with respect to $SU(2) \times U(1)$ forbids invariant mass terms for the exotic quarks, which can only acquire mass from weak symmetry breaking. We therefore expect exotic quark masses around or below the mass of the W-boson.

It seems very difficult to exclude the existence of these exotic quarks by theoretical arguments alone. The existence of exotics can be established for any given compactification. The theoretical problem, however, is to select the "true" compactification scheme. The possible existence of these half-integer charged hadrons, formed by exotic charge $+\frac{1}{6}$, $-\frac{5}{6}$ quarks with mass below ≈ 200 GeV, is rather an experimental issue. It should be noted that these exotic particles, which result from particular compactifications, are at present among the very few experimentally accessible predictions of higher dimensional theories. Since exotic quarks have the same strong interactions as standard quarks and differ only by their electric charge and couplings to Z^0 (and possibly $W^{\pm}$), their production cross sections at high-energy accelerators can be reliably calculated. Their signature involves stable half-integer charged hadrons. At present, the best lower bound on their mass comes from e^+e^- annihilation at PETRA/PEP, were stable particle searches using dE/dx measurements exclude exotic particles with mass less than about 20 GeV [‡1]. For the charge $-\frac{5}{6}$ quark, similar bounds are obtained from total cross-section measurements, i.e. R, and "onium" searches. With the ad-

[‡1] For a review see ref. [4].

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vent of the SLC/LEP experiments, higher bounds on the mass will be possible, or a clear observation of their existence! Possible signatures would include the normal behavior when a new quark threshold is passed, like a step in R after a resonance region of bound onium states, but also the direct observation of the exotic hadrons through a clear event topology and measurements as discussed below. $p\bar{p}$ collisions are also a possible source to produce these exotics, but here the present bounds (if any) are much less clear. The aim of this letter is therefore to investigate the problems of finding such new particles at the CERN and FNAL colliders.

Given the normal strong interaction of these exotic quarks, they can be produced at a hadron collider through the usual fusion processes, $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$, and the cross section calculated with standard QCD. For SPS and Tevatron energies, we show in fig. 1 the integrated cross section with the requirement of a minimum $p_\perp$ of the exotic quark

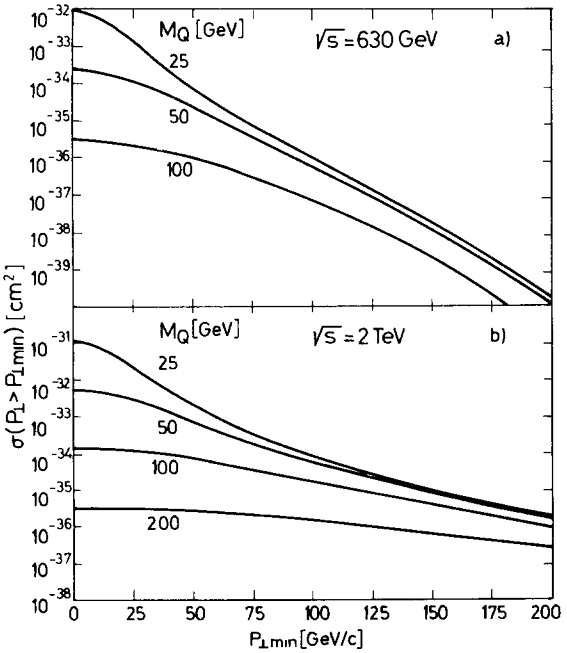

Fig. 1. Cross section of $p\bar{p} \to Q\bar{Q} + X$, eq. (1), requiring a minimum transverse momentum, $p_{\perp\min}$, of the exotic quark, Q, of mass, M_Q, at SPS (a) and Tevatron (b) collider energies.

$$\sigma(p_\perp \geqslant p_{\perp\min}) = \int dx_1 dx_2 d\hat{t} \sum_{i,j} f_i(x_1, Q^2) f_j(x_2, Q^2) \times \frac{d\hat{\sigma}_{i,j}}{d\hat{t}} \theta(p_\perp - p_{\perp\min}). \qquad (1)$$

The structure functions of ref. [5] were used together with the matrix elements from ref. [6] to obtain the results for a few different masses of the exotic quark. From the total cross sections (i.e. $p_{\perp\min} = 0$ in fig. 1) one can infer a total event sample of anything from a few events up to some thousand events, depending on the exotic quark mass, for the total integrated luminosity of close to 1 pb^{-1} obtained at the CERN collider so far. The production rate at a collider therefore seems to be at an observable level.

The fragmentation of the exotic quarks is expected to be similar to that of standard heavy quarks and our current knowledge of charm and bottom quark fragmentation can therefore be extrapolated using available fragmentation models. The energy fraction, $z = E_H/E_Q$, taken by the heavy hadron is thus expected to be very large. In fact, using the argument of Bjorken [7] gives an expected mean value $\bar{z} \approx 1 - 1/M_Q$, where M_Q is the heavy quark mass in GeV. The fragmentation function of Peterson et al. [8] gives a similar expectation whereas the Lund model [9] gives a somewhat harder spectrum. In all cases, however, a typical value of $\bar{z} \approx 0.99$ is expected for M_Q = 50 – 100 GeV. QCD evolution through gluon radiation will certainly cause some softening. However, since the source is a colour-triplet charge which only evolves from the off-shellness scale related to Q^2 of the hard interaction down to M_Q^2, this will not change the basic feature that the exotic hadron takes most of the jet energy, leaving very little to the remainder jet. To a good approximation the $p_{\perp\min}$ in fig. 1 will therefore apply also to the heavy hadrons. These will appear as isolated particles leading to a characteristic event topology: two stiff particles, back to back in the transverse plane, in a background similar to that of jet events (minimum bias plus extra activity due to large-Q^2 process). We note that both exotic hadrons will be stable and half-integer charged.

The missing energy, which is transformed into the heavy masses, cannot be directly used as a signature

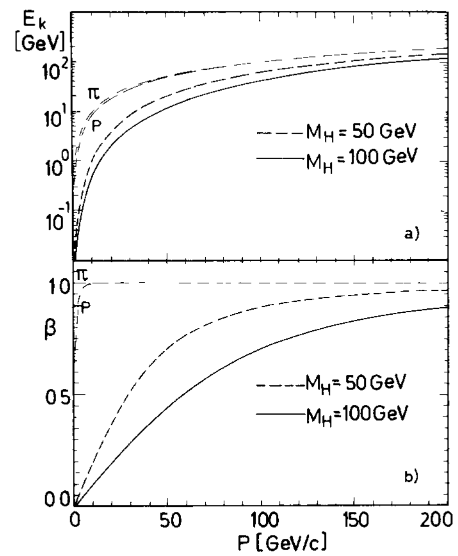

Fig. 2. Kinetic energy (a) and velocity (b) versus the momentum of particles of different mass.

since energy is usually lost by energetic particles going down the beam pipe. (Missing energy is balanced in the transverse plane to a good approximation.) Due to the large mass, the exotic hadrons will typically be non-relativistic and hence their kinetic energy, which can be absorbed in a calorimeter, be much smaller than their momenta as illustrated in fig. 2a. If produced rather close to threshold, their kinetic energy will not be enough to satisfy an $E_\perp$ trigger and such events would therefore presumably enter a minimum-bias sample. This would give an exceedingly small signal to background ratio of cross sections which would be very hard to overcome with off line selection criteria On the other hand, it does not cost very much in rate to require a minimum $p_\perp$ of, say, 50 GeV for M_Q = 50 GeV which would give the 10–20 GeV energy deposition needed for an $E_\perp$ jet trigger. This would reduce the background events by many orders of magnitude whereas the loss of exotic events can be acceptable. The details, depending on the required $p_{\perp\min}$ and exotic quark mass, can be read out from fig. 1.

The characteristic mismatch between the measured momentum and calorimetric energy is even more striking for a charge $\frac{1}{2}$ particle since its apparent momentum is twice the true one, when the charge is not measured For a charge $\frac{3}{2}$ particle, on the other hand, the mismatch is reduced by its smaller apparent momentum, two thirds of the true momentum. We also note that the energy deposited in a calorimeter will essentially be of hadronic nature and with an unusually small electromagnetic part as compared to normal jets. A possible search procedure would therefore be to use a jet sample and search for two isolated high-$p_\perp$ particles (back to back in azimuth) and confirm the energy–momentum mismatch. The background from normal jet events should be negligible, since that would require that both high-$p_\perp$ jets fragment into leading particles taking almost all jet energy, which is a very rare process already for a single jet. Moreover, the energy–momentum mismatch should in normal jet events only occur due to imperfections of the experimental equipment.

The slowness of the heavy exotics is illustrated in fig. 2b, which shows typical β values of 0.5 or even less. This makes time-of-flight measurements a very appropriate tool for identification. Since a very high time resolution is not needed it would even be possible to use a time-of-flight signal in a trigger condition. This would considerably improve detectability of stable hadrons produced near threshold. Alternatively, Čerenkov detectors could be used for identification.

Ionization measurements using dE/dx are, of course, also an interesting possibility. Fig. 3 is a typical example of the expected ionization as a function of momentum for particles of different mass and charge [10]. A problem here is that too slow heavy particles cause too much ionization which can not be properly measured in chambers designed for normal, light particles. Thus, the detailed properties of the chamber will be of importance.

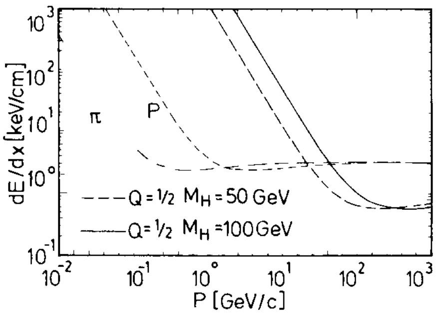

Fig. 3. Energy loss through ionization for exotic hadrons of momentum, p, compared to standard particles. (The vertical scale corresponds to a particular gas as an example.)

Based on the above estimated rates and signatures, it seems unlikely that the exotic hadrons discussed in this letter can be ruled out already from analyses made so far of collider data. Rather, a dedicated search is required, e.g. along the lines suggested above. That should, however, have the possibility to discover them or significantly improve the lower bounds on their mass. The event topology from production in e^+e^- at SLC or LEP would also be very clear: two leading, back-to-back, high-momentum tracks with only soft background tracks. Again all the other signatures, like energy–momentum mismatch, apply. The better instrumentation for particle identification available in these experiments would be an advantage. If discovered, these exotic quarks would also form onium states which could be studied at SLC/LEP. Due to the different couplings of exotics to photons and Z^0 these states could be distinguished from toponium. As for toponium, an interesting (but different) interference spectrum would arise for M_Q around half the Z^0-boson mass. It would also be possible to produce exotic quarks in an ep collider through the photon–gluon fusion process, but due to the softness of the gluon structure function the rate at HERA energies will not be competitive.

Besides their possible production in high-energy accelerators, exotic quarks would have been produced in the big bang. Almost all of them would be annihilated in the later evolution of the universe, unless an exotic baryon asymmetry [1] protects a certain fraction, in similarity with normal baryons. No estimate on the exotic baryon asymmetry (which may be much smaller than the standard one) is available. In addition, the concentration of exotics in terrestrial material would depend on other details, including their chemical behaviour. If exotic hadrons have a sufficiently high concentration they should be detected by searches for fractionally-charged particles in terrestrial materials, but unfortunately no estimate on this concentration seems possible at present.

What about their production in the atmosphere by high energy cosmic rays? For an exotic quark mass of 25 GeV we have estimated a rough upper bound of 10^{-2} exotics hitting the earth surface per m^2 and year. This estimate comes from folding the flux of high-energy cosmic-ray particles [11] with the mean number of exotics produced in proton–proton collisions as a function of energy (obtained from eq. (1) and a total pp cross section given by the fit in ref. [12]). This bound decreases very rapidly for higher quark masses, e.g. $\lesssim 10^{-4}$ exotics/m^2 y for $M_Q = 50$ GeV. We conclude that exotics cannot be observed in cosmic-ray experiments. The total number of exotics produced by cosmic rays during the existence of the earth is easily calculated and is much below possible detection by searches for non-integer charged particles in terrestrial material.

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