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COLOR SEXTET QUARKS AND NEW HIGH-ENERGY INTERACTIONS *

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Abstract

We review the implications of adding a flavor doublet of color sextet quarks to QCD. Theoretical attractions include - "minimal" dynamical symmetry breaking of the electroweak interaction, solution of the Strong CP problem via the "heavy axion" η_6, and Critical Pomeron Scaling at asymptotic energies. Related experimental phenomena, which there may be evidence for, include - production of the η_6 at LEP, large cross-sections for W^+W^- and Z^0Z^0 pairs and very high energy jets in hadron colliders, and a hadronic threshold above which high-energy "exotic" diffractive processes appear in Cosmic Ray events.

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1. INTRODUCTION

When added to QCD, a *flavor doublet* of color sextet quarks produces a number of very attractive features, including the following.

i) A dynamical "Higgs Sector" is provided[1,2] for the electroweak sector of the Standard Model in which sextet chiral symmetry breaking by QCD is the mechanism producing electroweak symmetry breaking. That is QCD color plays the role of technicolor and the electroweak scale is actually a QCD scale. The symmetry breaking corresponds to a "minimal" Higgs sector in that "$\rho = 1$".

ii) There is a unique resolution of the Strong CP problem[3] involving a very special axion - the η_6. This is an anomalously heavy axion that should be looked for, instead of the Standard Model Higgs particle, as a distinctive signal of sextet quark symmetry breaking.

iii) With two sextet flavors and six conventional triplet flavors we obtain a very special version of QCD with many theoretical virtues[4] - including unitary Critical Pomeron scaling at high energy. In this special version of QCD, "small instantons" can play an important dynamical role and may give exotic high energy diffractive interactions.

The existence of a "new" QCD sector at the electroweak scale, strongly coupled to electroweak states, would clearly have major implications for accelerator and Cosmic Ray Physics. In the latter part of this talk I shall review a number of "hints" from accelerator and Cosmic Ray experiments that this sector exists and may soon be discovered.

I would like to emphasize that from my theoretical perspective (which essentially comes from studying the consistency of QCD in the Regge limit) the sextet quark origin of a dynamical Higgs sector for the electroweak interaction is by far the most aesthetically attractive proposal for electroweak symmetry breaking.

2. ELECTROWEAK SYMMETRY BREAKING BY COLOR SEXTET QUARKS

In this Section we briefly review the essential features of sextet quark dynamical symmetry breaking. The original idea is due to Marciano[1] and a full development of the effective lagrangian formalism can be found in Ref. 2.

A massless flavor doublet (U, D) of color sextet quarks with the usual quark quantum numbers (except that the role of quarks and antiquarks is interchanged) is first added to the Standard Model *with no scalar Higgs sector.* For the $SU(2) \otimes U(1)$ anomaly to be cancelled there must also be other fermions with electroweak quantum numbers added to the theory, but we shall not consider this issue in this paper. There is a $U(2) \otimes U(2)$ chiral flavor symmetry. We anticipate that conventional chiral dynamics will break the axial symmetries spontaneously and produce four massless pseudoscalar mesons (Goldstone bosons), which we denote as $\pi_6^+, \pi_6^-, \pi_6^0$ and η_6 in analogy with the usual notation for mesons composed of u and d color triplet quarks.

The sextet pseudoscalars have the usual Goldstone boson couplings to the sextet axial currents, which in turn couple to the electroweak gauge fields. It then follows that the π_6^+, π_6^-, and π_6^0 are "eaten" by the massless gauge bosons and respectively become the third components of the W^+, W^- and Z^0. Consequently, QCD chiral symmetry breaking generates masses for the W^+, W^- and Z^0 with $M_W \sim g\ F_{\pi_6}$ where F_{π_6} is *a QCD scale.* An elementary picture of chiral symmetry breaking suggests a "Casimir Scaling" rule[5] which can be consistent with $F_{\pi_6} \sim 250$ GeV!

It is important that the η_6 is not involved in generating mass for the electroweak gauge bosons. Instead it is an axion[6], and remains massless until triplet quark masses are added via triplet/sextet four-fermion couplings. At first sight the η_6 also has a conventional axion mass ~ 100 keV. However, the η_6 is a very special axion composed of higher color quarks. The presence of sextet quarks very significantly slows the evolution of α_s above the electroweak scale and as a result, "small instanton" interactions within QCD are a much larger effect than naively anticipated. In particular such interactions can consistently[7,8] generate a much higher mass for the η_6.

The two photon decay rate for the η_6 can be calculated[9] from the anomaly and for a mass of, say, 60 GeV (we shall enlarge on the reasons for this choice below) the lifetime from this decay mode is comparable with that of the π^0. It is difficult to estimate the hadronic width, but if we use (m_{η_6}/F_{η_6}) as an order of magnitude estimate of the amplitude involved,then we conclude that the η_6 should still have a significant two photon decay mode (at perhaps the 1% level) even when the mass is as high as 60 GeV.

3. QCD WITH 6 COLOR TRIPLET AND 2 COLOR SEXTET QUARKS

As we noted in the Introduction, this theory has many interesting properties[4]. In particular we believe the version when *all the quarks are massless* is worthy of intense theoretical study - perhaps on the level which the large N limit of $SU(N)$ gauge theory is studied. There are strong arguments that the massless theory has an infra-red fixed-point, implying that the gauge coupling does not grow in the infra-red region. Therefore if the conventional non-perturbative properties of confinement and chiral symmetry breaking are present, they must arise from instanton interactions - which provide the only non-perturbative ingredient of the theory.

Properties of the massless theory should clearly underlie much of the physics that sets in above the electroweak scale, as the electroweak interaction couples in to QCD via the sextet quark sector. We have already noted the importance of short-distance instanton interactions in generating the η_6 mass. These interactions also play an important role in the development of the high-energy forward scattering behavior of the theory. Indeed, as we argue at length elsewhere[4], the infra-red fixed-point of the theory is directly reflected in Critical Pomeron scaling behavior in the asymptotic Regge limit. At the qualitative level, this suggests that instanton interactions can be thought of as directly involved in producing high-energy diffractive interactions at super-high energies.

More specifically, perhaps, an understanding of the Super-Critical Pomeron phase[4] suggests that we can visualize the high-energy expansion of a hadron as due to a thickening "surface" full of gauge fields rich in topological structure (that is there is an effective winding number vacuum condensate in this region). Another hadron scattering peripherally through the surface region feels this structure and a variety of instanton interactions within the scattering hadron are stimulated. This would include the stimulated production of sextet quark states. As we shall return to below, this implies that SSC physics may actually be dominated by the diffractive, and multiple Pomeron production, of electroweak states - that is multiple W's, Z^0's and η_6's.

4. POSSIBILITIES FOR DETECTION OF THE SEXTET QUARK SECTOR

In this and the next Section we discuss possible signatures of the sextet quark sector that may, perhaps, have already been seen or may be seen in the not too distant future. We begin with accelerator phenomena in this Section and then move on to Cosmic Ray events. Since most effects we consider are non-perturbative in origin, quantitative predictions are clearly difficult.

4.1 Perturbative *QCD* Production

This can be discussed quantitatively, but unfortunately is small. The common expectation is that the constituent sextet quark mass is of O(300) GeV. This is the mass that has to be used in perturbative production calculations, via gluon fusion in particular. Apart from color factors, this calculation is the same as the production of a heavy triplet quark. Not surprisingly the total cross section is less than 1 Pb. and so may well be too small to be seen at CDF. (Although one or two of the highest energy CDF "Zoo" events may, perhaps, be candidates!) It could be more interesting to look for higher-order gluon and quark composite operators that the sextet quark condensate will induce[10]. Evidence for these operators can, perhaps, already be seen in the very high-energy tail of the inclusive jet cross-section. The CDF data[11] is consistent with conventional QCD but can also accommodate contributions from such operators of just the order of magnitude[10] given by sextet quarks.

4.2 Non-Perturbative Production of Electroweak States

There will be non-perturbative production of W^+W^-, Z^0Z^0, $Z^0\gamma$, ... states in pp collisions which at high-energy will be dominantly given by (multi-) Pomeron exchange[12]. It is interesting that UA1 actually accumulated four $W + 2$ jet events[13] which are kinematically consistent with W^+W^- pair production and are quite distinct from the background events. These events suggest a W^+W^- production cross-section more than two orders of magnitude greater than that predicted by the Standard Model - with a conventional Higgs sector. CDF also has candidate W^+W^- and Z^0Z^0 events but not enough to indicate a cross-section significantly above the Standard Model prediction. Unfortunately the CDF detector does not cover the diffractive region where we might expect the non-perturbative production to be largest (and more easily distinguishable from background jet production).

As we mentioned above we can surely expect the diffractive production of electroweak states to be a major phenomenon at the SSC. Indeed it seems to me that it could very well become the dominant focus of SSC physics. In which case the full rapidity coverage given by a detector such as the FAD proposal[14], would be an essential requirement.

4.3 η_6 production

In principle, the η_6 could be a "normal" axion, but this is ruled out by comprehensive axion searches. Fortunately, as we have already indicated, small instanton interactions can be expected to produce an anomalously high mass. As we now discuss there are experimental hints that this may be as high as 60 GeV.

The L3 experiment at LEP has now seen[15] four events of the form $Z^0 \rightarrow l^+l^- + \gamma\gamma$ where the mass of the $\gamma\gamma$ pair is close to 60 GeV. If these events indicate a new massive particle then it has a significant width, which probably has to be hadronic in origin, and a major two photon decay mode. If there is a strongly interacting massive particle radiated by the Z^0 then it is clearly very tempting to identify it with the η_6. At first sight, however, there is a problem[3] in that rates calculated from the sextet quark anomaly[16] appear to be too low to be consistent with the L3 events. However, when the axion and Strong CP properties of the η_6 are studied in detail[3] we find that sextet quark QCD interactions need not be CP conserving. As a result there are CP non-conserving Goldstone boson amplitudes which can produce the L3 events consistently. The implications of identifying the L3 events with the η_6 will be discussed at length in Ref. 3.

If the η_6 has a mass of O(60) GeV and our diffractive enhancement picture is correct, we would expect a significant cross-section for diffractive η_6 production at both the CERN and Fermilab colliders. This could perhaps be correlated with the observation[17] of a large real part of the forward scattering amplitude by the UA4 experiment at CERN. If the scattering is at energies well above all thresholds, the real part is related to the total cross-section by a derivative dispersion relation. Since the total cross-section is rising only relatively slowly in the same energy range, the UA4 result is inconsistent with this relation. The only viable explanation[18] is that there is a major new threshold in the strong interaction. This threshold has to be localized at roughly $\sqrt{s}$ 500 GeV and could indeed be diffractive production of the

η_6. We shall find further support for this suggestion in the Cosmic Ray results discussed in the next Section.

5. HIGH-ENERGY SEXTET QUARK INTERACTIONS AND COSMIC RAY PHYSICS

The argument that there is a major change in the nature of the strong interaction at very high Cosmic Ray energies has been made consistently over the last ten years, particularly by the Chacaltaya emulsion-chamber group[19]. The proportion of "exotic" events apparently rises with energy and may be as high as 50% for $\sqrt{s} \gtrsim$ 10 TeV. That the threshold for the lowest energy exotic events is around $\sqrt{s} \sim 500$ GeV was a major part of the argument[20] for raising the CERN collider energy to search for exotic events. The "excess muon" point source events[21] also suggest a major change in the γp interaction for $\sqrt{s} \gtrsim$ 1 TeV. Qualitatively these changes are consistent with what we expect from a new (very) strongly-interacting sector of QCD. Also it is generally emphasized by the Cosmic Ray experimentalists that the exotic events are almost invariably diffractive in nature. This certainly fits with our expectation that diffraction will play a major role in the production of sextet quark states. It is hard to be quantitative but we can make the following observations as directly relevant to our previous discussion.

The lowest energy exotics, the "Geminions" and "mini-Centauros", have

i) a threshold of $\sqrt{s} \sim 500$ GeV, ii) a common "fireball" mass (originally set at 30 GeV but now apparently higher for the more distinctly exotic events), iii) a cross-section which is several per cent of the total cross-section, iv) a diffractive rapidity distribution.

It is clearly tempting to identify these exotics with diffractive production of the η_6. We could then match the mini-Centauros with the hadronic decays of the η_6 and the Geminions with two-body electroweak decays (including 2γ decays)[3]. These events are also characterized by large transverse momentum, as might be expected from diffractive sextet quark interactions involving small instantons. The anomalously low γ - hadron ratio of mini-Centauros could be due to the changing nature of the γp interaction - which we shall discuss further below.

If we consider the next class of exotic events to appear, the Chiron and Centauros, they share the following properties

i) a threshold of $\sqrt{s} \sim 2$ TeV, ii) a common fireball mass of 200 - 300 GeV, iii) a significant part of the cross-section, iV) a diffractive rapidity distribution.

An obvious question is whether these exotics could be associated with sextet quark states. We expect an array of sextet "baryons" (involving one sextet quark and two triplet antiquarks) and vector "mesons" in the 300 - 1,000 GeV mass range. It is possible that the hadronic decays of these states are dramatic (involving small instantons) and are what is seen in the higher energy exotic events.

If sextet quark interactions can account for all exotic high-energy interactions, then a significant change in the γp interaction must be part of the picture. This is required to explain all of the anomalous shower development that is seen and the consequent identification of anomalous γ - hadron ratios in exotic events. The photon does couple in directly to the sextet quark sector and we anticipate a very strong coupling of the Pomeron to sextet states. This will produce a much larger γp hadronic cross-section. Whether this will be sufficient to explain the anomalous characteristics of the exotic events - as well as the excess muon point source events[21] - is, not surprisingly, a hard question to answer.

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