NEW STRONG INTERACTIONS ABOVE THE ELECTROWEAK SCALE

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Abstract

Theoretical arguments for a new higher-color quark sector, based on Pomeron physics in QCD, are briefly described. The electroweak symmetry-breaking, Strong CP conservation, and electroweak scale CP violation, that is naturally produced by this sector is also outlined.

A further consequence is that above the electroweak scale there will be a radical change in the strong interaction. Electroweak states, in particular multiple W’s and Z’s, and new, semi-stable, very massive, baryons, will be commonly produced. The possible correlation of expected phenomena with a wide range of observed Cosmic Ray effects at and above the primary spectrum knee is described.

Related phenomena that might be seen in the highest energy hard scattering events at the Fermilab Tevatron, some of which could be confused with top production, are also briefly discussed.

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1. INTRODUCTION

The physics of very high energy Cosmic Rays, as seen in Mountain Emulsion Chambers and Extensive Air Showers, is predominantly that of strong interaction fragmentation and diffraction. It is well known in the Cosmic Ray community that a significant number of effects now suggest the existence of new strong interaction physics at energies around $10^{16}$ eV or higher. The most radical proposal being[1, 24] that the famous “knee”, in the induced incoming energy spectrum, around this value is actually evidence for new physics rather than a discontinuous change in the primary spectrum. The corresponding center of mass threshold for hadron-hadron scattering is $\sqrt{s} \sim 3 - 5$ TeV. This implies that the new physical processes can probably not be seen directly at the Fermilab Tevatron but, as I shall discuss, the physics involved might be glimpsed in the highest energy virtual processes.

I have studied the QCD Pomeron responsible for diffraction for many years, and for some time have advocated the theoretical necessity for a new, higher-color, quark sector. From my analysis[2] this new sector is directly required for the consistency of the Pomeron with both confinement and perturbative QCD at high-energy. Remarkably such a sector can replace the unaesthetic Higgs sector of the Standard Model (in partial analogy with technicolor) and provide an essentially complete mechanism for mass generation in the electroweak sector. This links the strong and electroweak interactions in a direct manner and, in particular, implies that the electroweak scale is explained as a second QCD scale. As I have studied this possibility more and more seriously, I have gradually realized that other deep puzzles of the Standard Model may also be resolved. For example, the problems of Strong CP Conservation and CP Violation at the Electroweak Scale.

In this talk I will first explain qualitatively why the new quark sector is required in QCD and also describe the dynamical electroweak symmetry-breaking and CP properties that result. I will then spend the remainder of the talk elaborating on the essential feature for this conference. That is, not very far above the electroweak scale there will be a radical change in the strong interaction. Electroweak states, in particular multiple $W'$s and $Z'$s, and new semi-stable baryons, will be commonly produced. We anticipate that diffractive production of the new states will be a major (if not the major) effect. Clearly this will dramatically change the nature of Cosmic Ray showers and the states they produce above such energies. Although very difficult to predict in any detail, I will suggest that the new phenomena to be expected have the right characteristics to explain, qualitatively, a wide range of observed Cosmic Ray effects, including the following.

- Strong attenuation of family production, as observed in emulsion chambers, together with a sharp change in the electromagnetic and hadronic energy spectra.
- Small $X_{max}$ for high-energy air showers with $E^0 \sim 10^{17}$ eV together with a fast rise of $X_{max}$ as the energy increases.
• Shorter “hadronic” interaction length in emulsion and lead chambers.

• Anomalous penetration in the atmosphere and in detectors, often involving the production of intense “halos”.

• Coplanarity of multi-halos.

• Large $p_\perp$ production of “Centauros” - with low electromagnetic energy, and “Chirons” - with apparent anomalously low $p_\perp$ in secondary showers.

• Excess of (underground) muon pairs with large separation.

• Large zenith angle excess of high-energy air showers and azimuthal asymmetry in $\gamma$ and hadron family production.

In general the situation seems very interesting and a reasonable case can be made that the type of modification of the strong interaction that I am arguing for is actually being observed in the highest energy Cosmic Rays. Of course, many of the above Cosmic Ray effects suffer from low statistics and it will remain essential that they be observed in accelerator experiments if they are to be confirmed and studied. The LHC will cover most of the relevant energy range but it is a decade away from operating. As I discuss at the end of the talk, it is also possible that the accumulating number of very high energy hard scattering events at the Fermilab Tevatron (mostly involving photon and weak vector boson states) could be a glimpse of the physics involved. Indeed this physics might well be closely correlated with top production and there could be confusion, experimentally, between new and expected production processes.

2. POMERON FIELD THEORY

In pre-QCD days the Pomeron was a phenomenological object - a Regge pole which (essentially) was thought to reflect the low $k_\perp$ multiperipheral production of multiple pions (with, say, $< n > \sim 10 - 20$). As illustrated in Fig. 1,

$$\sigma_T = \Sigma \int d\Omega_n |A_n|^2 \sim s^{\alpha_P(0) - 1}$$

so that $\sigma_T \sim C$ requires $\alpha_P(0) = 1$. **Pomeron** (reggeon) **Field Theory** had both a phenomenological and, via reggeon unitarity, a theoretical basis\[3\] as an effective field theory accounting for all the additional diffractive and absorptive effects that unitarity requires must accompany multiperipheral pion production. High-mass diffraction determines the magnitude of the triple Pomeron coupling. Multi-Pomeron diagrams can be thought of as representing multiplicity fluctuations. That is, an N-Pomeron state appearing on some part of the rapidity axis is associated with a multiplicity fluctuation of N times the average
multiplicity in that rapidity interval. The origin of some reggeon graphs is illustrated in Fig. 2.

The renormalization group can be applied to Pomeron Field Theory and, with a triple Pomeron coupling, there is a Critical Pomeron solution for $\alpha_{PI}(0) = 1$. This gives $\sigma_T \sim (\ln s)^\eta$ where $\eta$ is an anomalous dimension. The Critical Pomeron is the only known theoretical description of rising total cross-sections which satisfies all $s$ and $t$ - channel unitarity constraints.

Within Pomeron Field Theory we can study what happens if we initially violate unitarity by setting $\alpha_{PI}(0) > 1$. The result is a new Super-Critical Pomeron phase in which there is a Pomeron condensate - giving rise to the vacuum production of Pomerons! At first sight, it is difficult to understand how the vacuum production of Pomerons could possibly have a physical interpretation. However, a detailed study of the structure of the induced graphs, the transverse momentum singularities that appear, and the resultant reggeon unitarity properties, leads to the following remarkable result.

Vacuum production of Pomerons directly produces additional particle pole factors in reggeon graphs that correspond to vector reggeon intermediate states. Consequently, the phase-transition when $\alpha_{PI}(0) > 1$ involves the conversion of the divergences in rapidity (due to $\alpha_{PI}(0) > 1$) into particle divergences in transverse momentum. In effect, if we try to make the total cross-section increase more rapidly than allowed by unitarity, a vector particle $V$ is “deconfined” and appears in the theory coupling pair-wise to the Pomeron.

The vector reggeon trajectory $\alpha_V(t)$ is exchange-degenerate with the Pomeron trajectory and, away from the critical point, the physical intercepts satisfy $\alpha_{PI}(0) = \alpha_V(0) < 1$. As a result, in both the Sub-Critical and Super-Critical phases, we have $\sigma_T \rightarrow 0$ asymptotically. This implies that to obtain a rising cross-section the Pomeron must be Critical.

The Super-Critical Pomeron was discovered independently of QCD but a fundamental question is, of course, what is the physical interpretation (if any) of the Pomeron phase transition in QCD? Or, equivalently, can the vector particle $V$ be related to a (deconfined) gluon?

3. THE POMERON PHASE-TRANSITION IN QCD

In the multiperipheral model it is clear that adding more hadron states increases $\alpha_{PI}(0)$. Therefore, if there is a Regge pole Pomeron in QCD, we anticipate that adding quarks moves the Pomeron closer to criticality and that the Critical Pomeron might be related to QCD with the “maximum” number of quarks. All quarks become (close to) massless in the asymptotic Regge limit, and so we are led to ask - can the physics of QCD with a large number of massless quarks be related to the Pomeron phase-transition?
Several properties of (massless) QCD suggest that the Critical Pomeron does indeed occur when the number of flavors \( N_f \) is a “maximum”. Since these can be described without introducing the technology of Reggeon Field Theory we briefly describe them here. \( N_f = N_f^{\text{max}} = 16 \) is the maximum value before asymptotic freedom is lost and (presumably) gluons are deconfined. (The deconfinement implies, of course, that there is a phase transition but can we identify the Critical Pomeron transition?) Consider first the behavior of the \( \beta \)-function as a function of \( N_f \). It is very likely\(^2\) that at \( N_f = N_f^{\text{max}} \) (and probably only at this value) the \( \beta \)-function develops an infra-red fixed-point, as illustrated in Fig. 3.

The scaling properties, and in particular, the variety of anomalous dimensions that develop at this fixed-point clearly could be directly related to the scaling properties of the Critical Pomeron. Indeed, it can be shown\(^6\) that in the limit of zero meson mass (which we assume to correspond to the limit of zero quark mass in QCD), the Critical Pomeron forward diffraction peak behaves as illustrated in Fig. 4. That is the diffraction pattern collapses into a simple peak that has\(^6\) the character of a massless vector singularity with an anomalous dimension, suggesting directly a relationship with a massless, fixed-point, vector theory.

Also, when \( N_f = N_f^{\text{max}} \) (and only at this value), the first term in the \( \beta \)-function is small enough\(^7\) that adding a triplet (“Higgs”) scalar to the theory retains asymptotic freedom of both the gauge coupling and the scalar coupling. This implies that for this “maximum” number of quarks, the (dynamical?) Higgs mechanism can break the gauge symmetry, from SU(3) to SU(2), without destroying the short-distance properties of the theory. Consequently a vector reggeon V, i.e. a massive gluon reggeon, can enter the theory smoothly (with no \( k_\perp \) cut-off in particular) only when \( N_f = N_f^{\text{max}} \).

Since the entry of V into the theory characterises the Super-Critical Pomeron we have another independent argument that \( N_f = N_f^{\text{max}} \) is the critical point.

Of course, we expect confinement to be crucial for the emergence of a multiperipheral like Pomeron related to pion production etc.. The study of confinement in the Regge limit is a major topic. After an elaborate technical analysis utilising reggeon diagrams, it can be shown\(^2\) that within QCD

- quarks play a crucial role in the simultaneous emergence of confinement and a Regge pole Pomeron in the small \( k_\perp \) high-energy regime
- the energy-dependence of small \( k_\perp \) physics (i.e. \( \alpha_s(0) \)) is strongly dependent on both \( N_f \) and the \( k_\perp \) cut-off and the Critical Pomeron occurs without a cut-off only when \( N_f = N_f^{\text{max}} \).

To remove the \( k_\perp \) cut-off and obtain a smooth matching with QCD perturbation theory at large \( k_\perp \), we must have a cross-section that does not go to zero asymptotically (i.e.
\( \alpha_s(0) = 1 \), since this is what the perturbation expansion gives. Therefore, for confinement and QCD perturbation theory to coexist in the high-energy region, we must obtain the Critical Pomeron as the large \( k_\perp \) cut-off is removed. Since this requires \( N_f = N_f^{\text{max}} \), a further quark sector must exist!!

It is very important, however, that (assuming six flavors are known to exist)

- the further quark sector need not be 10 more flavors of color triplet quarks. \( N_f = N_f^{\text{max}} \) is also produced by an additional flavor doublet of color sextet quarks.

4. ELECTROWEAK SYMMETRY BREAKING, ELECTROWEAK SCALE INSTANTON INTERACTIONS, AND CP-VIOLATION

From the perspective of QCD Pomeron physics, it is a remarkable coincidence that two flavors of color sextet quarks can provide a natural form of dynamical symmetry-breaking for the electroweak interaction which meshes perfectly with the observed experimental features. Indeed this provides a self-contained motivation for introducing the higher color quark sector which we can briefly outline as follows.

Consider adding to the Standard Model (with no scalar Higgs sector), a massless flavor doublet \((u_6, d_6)\) of color sextet quarks with the usual quark quantum numbers, except that the role of quarks and antiquarks is interchanged. 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 here except to note that this could be the color octet leptoquarks discussed below. We consider first the QCD interaction of the massless sextet quark sector. There is a \( U(2) \otimes U(2) \) chiral flavor symmetry. QCD chiral dynamics will break the axial symmetries spontaneously and produce four massless pseudoscalar mesons (Goldstone bosons), which we denote as \( \pi^+_6, \pi^-_6, \pi^0_6 \) and \( \eta_6 \), in analogy with the usual notation for mesons composed of \( u \) and \( d \) color triplet quarks.

As long as all quarks are massless, QCD is necessarily \( CP \) conserving in both the sextet and triplet quark sectors. Therefore, in the massless theory we can, in analogy with the familiar treatment of flavor isospin in the triplet quark sector, define sextet quark vector and axial-vector currents \( V_\mu^r \) and \( A_\mu^r \) which are “isotriplets” under the unbroken \( SU(2) \) vector flavor symmetry and singlet currents \( v_\mu \), \( a_\mu \). The pseudoscalar mesons couple “longitudinally” to the axial currents, that is

\[
< 0|A^r_\mu|\pi^*_6(q) > \sim F_{\pi_6} q_\mu, \quad < 0|a_\mu|\eta_6(q) > \sim F_{\eta_6} q_\mu
\]  

\( (2) \)
while the vector currents remain conserved. (Note that $a_{\mu}$ should actually contain a small admixture of the triplet quark flavor singlet axial current if it is to generate the $U(1)$ symmetry orthogonal to that broken by the QCD $U(1)$ anomaly).

We consider next the coupling of the electroweak gauge fields to the sextet quark sector. The massless $SU(2)$ gauge fields $W^{\tau}_{\mu}$ couple to the isotriplet sextet quark currents in the standard manner, that is

$$\mathcal{L}_I = g W^{\tau\mu} (V^{\tau}_{\mu} - A^{\tau}_{\mu})$$

(3)

It follows from (2) and (3) that the $\pi^{+}_6$, $\pi^{-}_6$ and $\pi^{0}_6$ are “eaten” by the $SU(2)$ gauge bosons and (after the hypercharge interaction is included) 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 $M_W \sim g F_\pi$ where $F_\pi$ is a QCD scale. We anticipate that the relative scales of triplet and sextet chiral symmetry breaking are determined by the “Casimir Scaling” rule[8], i.e. if $C_6$ and $C_3$ are sextet and triplet Casimirs respectively, then

$$C_6 \alpha_s (F_\pi^2) \sim C_3 \alpha_s (F_\pi^2)$$

(4)

which is consistent with $F_\pi \sim 250$ GeV!

We conclude that a sextet sector of QCD produces a special version of “technicolor” symmetry breaking in which the electroweak scale is naturally explained as a second QCD scale. Also since we are completely restricted to a flavor doublet the form of the symmetry-breaking is automatically equivalent to that of an $SU(2)$ Higgs sector and so

$$\rho = (M_W^2/M_Z^2 \cos^2 \theta_W) = 1$$

(5)

as required by experiment.

Therefore introducing a sextet quark sector not only produces a matching of the asymptotic freedom and confinement properties of QCD via the Critical Pomeron, but also gives a natural solution to the major problem of today’s Standard Model i.e. the nature of electroweak symmetry breaking. The sextet sector may, as we now discuss, also be deeply tied up[10, 11] with the issue of Strong CP conservation.

The $\eta_6$ is not involved in generating mass for the electroweak gauge bosons, but instead remains as a Goldstone boson associated with a $U(1)$ axial chiral symmetry. It is therefore an axion[12] in the original sense of the Peccei-Quinn mechanism[13] and it remains massless until triplet quark masses are added to the theory. In the present context, this involves the addition of triplet/sextet four-fermion couplings (that should ultimately be traceable to a larger unifying gauge group), which, when combined with the sextet quark condensate, provide triplet quark masses. That CP remains conserved by QCD triplet quark
interactions then follows from the original Peccei-Quinn argument utilising the sextet axial $U(1)$ symmetry.

At this stage another very important property of QCD with $N_f = N_{f}^{\text{max}}$ is crucial. It seems that renormalon singularities are completely absent in the Borel plane\cite{2, 14}. This implies that perturbation theory is much more convergent and that **instanton interactions are both infra-red finite and provide all the non-perturbative physics** of the theory. Instanton interactions are therefore well-defined at the lowest infra-red scale of the theory, i.e. the electroweak scale. Combining this with the extremely slow evolution of the gauge coupling, the instanton interactions are then enhanced by integration over an extremely wide size range (for the instanton involved). Consequently the $\eta_6$ can acquire a large, i.e. electroweak scale, mass as a result of electroweak scale (and higher) color instanton interactions\cite{11} and, unlike a conventional Peccei-Quinn axion, is certainly not ruled out experimentally. Indeed it may even have been seen\cite{10}. Clearly all of the particular properties of QCD with color sextet quarks play an intrinsic role in this very special resolution of the Strong CP problem.

A rather complicated set of fermion vertices is actually generated by the electroweak scale instanton interactions. Because of the distinct Casimirs involved, the singlet current

$$J_{\mu}^{0} = a_{\mu}^{6} - 5a_{\mu}^{3}\quad (6)$$

is conserved in the presence of instantons (6 and 3 now denote sextet and triplet currents respectively). Consequently the minimum instanton interaction involves one quark/antiquark pair of each triplet flavor and five pairs of each sextet flavor. Combining this interaction with the existence of both sextet and triplet chiral condensates (and, also, four-fermion vertices coupling triplets and sextets) a wide assortment of fermion vertices is produced. As we discuss further in the next Section, we expect that these vertices will play a major role in strong interactions above the electroweak scale.

Finally we note that **the sextet sector may also be responsible for CP violation at the weak scale**. Because the sextet sector has no axion the QCD interactions at this scale will naturally be **“Strong CP-violating”**. The familiar triplet quark hadrons will contain a small admixture of sextet quark states - which could provide their $CP$ violating interactions.

Before we go on to the the new strong interactions and their consequences for Cosmic Ray physics, we would like to emphasize the (unconventional) implication of the foregoing arguments. Namely that understanding the intricacies of the strong interaction may actually provide answers to remaining problems of the weaker interactions. Or equivalently

- **the QCD Pomeron may be the Key to Many of the Remaining Puzzles of the Standard Model**
5. THE NEW STRONG INTERACTIONS

Above the sextet chiral scale, that is the electroweak scale, the sextet sector will be a major part of the QCD interaction. $QCD_{\max}$ (that is QCD with $N_f = N_f^{\max}$ - via the triplet and sextet sectors) is a very different gauge theory to those conventionally studied. The gauge coupling is relatively small and effectively does not run. While the sextet sector can, presumably, be integrated out to give conventional QCD at low energies, at high energy we can expect very different behavior. Some “non-perturbative” physics will perhaps be understood via conventional non-perturbative QCD ideas in terms of sextet flux tubes etc.. However, many non-perturbative effects will surely be directly dependent on the multitude of higher-order (instanton) fermion interactions involving sextet quarks. (We have emphasized that these interactions are enhanced by the gauge coupling not running). As illustrated in Fig. 5, these interactions will generate high-order vertices coupling $W$’s, $Z$’s, and $\eta_6$’s, with

\[
\Gamma_{mW, nZ, r\eta_6} \sim \frac{F_{\eta_6} \text{(momentum scale)}^2}{\langle q\bar{q}_6 \rangle} \Gamma_{(m-1)W, nZ, r\eta_6}
\]

\[
\sim \frac{F_{\eta_6} \text{(momentum scale)}^2}{\langle q\bar{q}_6 \rangle} \Gamma_{mW, (n-1)Z, r\eta_6}
\]

\[
\sim \frac{F_{\eta_6} \text{(momentum scale)}^2}{\langle q\bar{q}_6 \rangle} \Gamma_{mW, nZ, (r-1)\eta_6}
\]

where $\langle q\bar{q}_6 \rangle$ is the sextet condensate and $\langle q\bar{q}_6 \rangle^{\frac{1}{3}} \sim F_{\eta_6} \sim 250$ GeV.

The $W^{\pm}$, $Z^0$ and $\eta_6$ are the “PIONS” of the sextet sector and, as we have just described, they will be multiply produced, via a “hard” interaction at the electroweak scale. Since the mass and decay properties of the $\eta_6$ are not well understood[10] and it has, of course, not yet been discovered, we will concentrate mainly on multiple $W$ and $Z$ production.

Because of the Casimir effect, we anticipate that sextet states will have a stronger coupling to gluons, and hence to the Pomeron, than does the triplet sector. Therefore

- **sextet states will have larger hadronic cross-sections than triplet states (i.e. conventional hadrons)**

My work[2] on high-energy hadrons interacting via the Pomeron can be heuristically understood if we visualize a hadron as a conventional bag containing quarks but with the surface containing a “topological condensate” due to instanton interactions and expanding as illustrated in Fig. 6.
In first approximation, the Pomeron can then, as illustrated, be thought of as one gluon exchange within the overlapping topological gauge fields of the scattering hadrons. (Note that this automatically gives the “additive quark model” result that the Pomeron couples directly to a single quark in a hadron).

The topological gauge fields of the hadrons will also, via instanton interactions, be responsible for multiple $W$ and $Z$ production accompanying the perturbative gluon interaction. Therefore we conclude that a major component of the new strong interactions above the electroweak scale will be

- **diffractive production, with very high transverse momentum, of states containing large numbers of $W$’s and $Z$’s.**

This will be one major ingredient of our discussion of Cosmic Ray effects.

Next we note that the sextet quark sector will produce new BARYONS of the form

$$\bar{q}_6 q q, \bar{q}_6 q \bar{q}, \bar{q}_6 q_6 q, q_6 q_6 \bar{q}, \bar{q}_6 q_6 \bar{q}_6, q_6 q_6 q_6,$$  \hspace{1cm} (8)

There will also be VECTOR MESONS of the form

$$q_6 q_6$$  \hspace{1cm} (9)

The sextet quark constituent mass is presumably of the same order of magnitude or a little larger than the chiral scale and so for definiteness we will take it to be $\sim 400$ GeV. Clearly the lightest new states will be the BARYONS containing just one sextet quark. Their mass will be very close to the sextet mass i.e. $\sim 400$ GeV and since, within $QCD_{max}$, sextet and triplet baryon numbers are separately conserved, they will be very stable. We refer to BARYONS containing two (triplet) quarks as $P$’s and those containing two antiquarks as $\bar{P}$’s. The VECTOR MESONS will decay into the PIONS of the theory and so will give resonance production of $W$’s, $Z$’s and $\eta_6$’s at the TeV scale. The higher mass BARYONS will presumably decay into $P$’s and $\bar{P}$’s (together with appropriate combinations of normal hadrons).

For the next Section it will be crucial that the $P$’s and $\bar{P}$’s are **sufficiently stable** that sometimes (but not always) they survive a trip (with collisions) from near the top of the atmosphere down to mountain-top detectors.

If the $P$’s and $\bar{P}$’s are to decay, there must be a further (unifying) interaction coupling the two distinct quark sectors. At first sight this could be a high mass (GUT) gauge boson.
But the absence of proton decay probably makes it very difficult to construct such a theory consistently if the BARYONS are to decay much faster than protons! An alternative\cite{9} is that within the unified theory, there are further color octet quarks ($q_8$) (these could be “leptoquarks”) that enter at a mass scale just a few orders of magnitude above the electroweak scale. At this scale the unified theory can be asymptotically free even though the QCD subsector will not be. If the unified theory is chiral then in general two-fermion condensates are not gauge invariant. Gauge-invariant condensates must contain at least four fermion fields and so it is natural\cite{14} to expect that, at the new high mass scale, condensates of the form

$$\langle q_8 q_8 q_6 q_3 \rangle$$

(10)

will exist. QCD instanton interactions, at this scale, will then produce the appropriate sextet quark decays. We therefore assume that

- $P$’s and $\bar{P}$’s are “semistable” with a decay rate determined by a mass scale much larger than the electroweak scale. We anticipate that their decay modes will include states containing multiple $W$’s and $Z$’s.

Clearly BARYONS can be pair-produced diffractively by the Pomeron (in particular, via an instanton interaction), also VECTOR MESONS can be produced with an accompanying $W$’s and/or $Z$’s. From the experimental evidence on the diffractive production of strange baryons\cite{15} illustrated in Fig. 7, we can assume that this production process will have some important properties, which we can explain as follows.

Because the Pomeron couples predominantly to a single quark in a proton, two constituent quarks persist in the forward direction of the initial proton (with around 90% probability) during any diffractive excitation process. If a new forward going baryon is to be formed then this is achieved by the vacuum production of additional quark-antiquark pairs in the center of mass of the scattered quark and the forward going diquark system. (This process can be an instanton interaction). There are two consequences of this production mechanism which will carry over directly into the diffractive production of BARYONS.

Firstly, because only a single quark can be replaced in the fast proton if a BARYON-ANTIBARYON pair is produced

- there is a charge bias in the production of the forward produced BARYON - it is necessarily positively charged or neutral. Correspondingly the charge of the ANTIBARYON state produced away from the forward direction is either negative or neutral.
Secondly, if all vacuum pairs involved are produced (almost) at rest in the center of mass of the scattered quark and diquark system then, as is illustrated by the data for diffractive production of $\Lambda^0\bar{\Lambda}^0$ pairs shown in Fig. 7,

- **the full diffractively produced state is approximately coplanar - it lies in the plane formed by the momenta of the forward going fast BARYON and the (ANTI-)BARYON with the smallest forward momentum.**

With all of the properties highlighted in this Section in hand we can now try to explain at least part of the wide range of Cosmic Ray exotica.

6. COSMIC RAY EVIDENCE FOR THE NEW STRONG INTERACTIONS.

In this Section I will go through the phenomena I listed in the Introduction, giving a brief summary of the experimental results and then describing their interpretation in terms of the physics of the last Section. Since I am not an expert I may well have misunderstood some of the phenomena involved. If so I apologize to the authors involved.

**Strong attenuation of family production, as observed in emulsion chambers, together with a sharp change in the electromagnetic and hadronic energy spectra.**

Such effects have been seen by the Chacaltaya and Pamir collaborations and more distinctively in the highest energy results of the HADRON experiment at Tien-Shan. Figs. 8(a) and 8(b) show that the combination of low family flux and small energy spectrum indices for constituent showers in the Chacaltaya/Pamir data\cite{16} is not fit by any of the conventional models. As shown in Fig. 8(c), the discrepancy is less if a heavy nuclei primary composition is assumed.

Fig. 9(a) shows a possibly related effect in the data\cite{1} from the HADRON experiment. The $\gamma$ spectrum of shower cores scales up to a certain energy and then softens as the energy increases. As is shown, the softening could be reproduced by a heavy primary composition but the overall intensity would be much too high. Fig. 9(b) shows that the assumption of a heavy primary composition is inconsistent with the muon multiplicity distribution obtained at Tien-Shan.

The change of the $E_\gamma$ spectrum suggests the existence of a physical threshold around the knee energy. It also implies that, for some fraction of the Chacaltaya/Pamir events, the primary energy may be higher than given by conventional physics models. Therefore new physics above the threshold may be involved in these events also.
My explanation of these phenomena is close to that already suggested by those working on the HADRON experiment[1]. At high enough energies, production of the heavy, semistable, $P$’s and $\bar{P}$’s will be a significant part of the diffractive and fragmentation cross-sections. Since these BARYONS are semi-stable they will propagate for large distances within the shower, sometimes reaching the detector. The evolution of that part of the shower energy not in the heavy BARYONS will be normal but will clearly produce far fewer gamma and hadron families. This effect is labeled “fragmentation region disappearance” by Nikolsky[1] who argues that the particles involved should have a mass $\geq 400$ GeV. This explanation achieves the same effective reduction of primary energy as heavy nuclei primaries would do, but without the high multiplicity muon production that is not seen in Fig. 9(b).

A heavy primary composition for energies around $10^{16}$ GeV is also incompatible with the Soudan 1 underground muon multiplicity[17]. Recent MACRO data[18] shown in Fig. 10(a) leads to a similar conclusion. As is shown in Fig. 10(b), the high multiplicity tail of this distribution is determined by the highest primary energies, whatever (conventional physics) composition model is utilised. The absence of a large number of high multiplicity muon events is clearly a major problem for any explanation of very high energy Cosmic Ray phenomena that appeals to a large heavy nuclei composition.

Small $X_{max}$ for high-energy air showers with $E^0 \sim 10^{17}$ eV together with a fast rise of $X_{max}$ as the energy increases.

This is the Fly’s Eye result[19]. As illustrated in Fig. 11, results for the lowest energies i.e. $E^0 \sim 10^{17}$ eV, give a sufficiently low average value for $X_{max}$ that a very strong heavy nuclei composition has to be used to fit the data with conventional physics models. However, as the energy rises this average increases too fast and the distribution changes too much for a single composition model to fit the data. It is necessary to vary the composition with energy as illustrated. The initial heavy nuclei composition is again at variance with the lack of high-multiplicity underground muon events mentioned above.

My explanation here is, in part, the same as for the previous effect. At the lower end of the energy range the production of the heavy, semistable, BARYONS will reduce the development of the shower and the consequent average $X_{max}$ in the same manner as the heavy nuclei composition. However, as we get to energies high compared even to the sextet scale we can expect that, in analogy with the triplet sector, high multiplicity PION states will be the dominant sextet states produced. That is the production of $W$’s, $Z$’s and $\eta_b$’s will dominate. Since these states are all unstable the showers will develop more like normal proton showers. This could produce naturally the required energy dependence of the $X_{max}$ distribution without any dramatic change in composition.
Shorter “hadronic” interaction length in emulsion and lead chambers.

The results of the Chacaltaya/Pamir collaboration[20] are shown in Fig. 12. Both in the Chacaltaya emulsion chambers and in the Pamir lead chambers there is a pronounced decrease in the hadronic interaction length in the highest energy showers.

I attribute this in part to the higher hadronic cross-section of those sextet BARYONS that reach the detector. Also multiple $W$, $Z$ and $\eta_6$ intermediate states will produce major decay modes involving heavy flavors, leptons, and photons, which may be partly responsible for the effect.

Anomalous penetration in the atmosphere and in detectors, involving the production of intense “halos” in the highest energy showers.

Examples of events which have extreme penetration in lead[20] and in emulsion chambers[16] are shown in Fig. 13. Some of them continue producing new showers down to an extraordinary depth. At the highest energies the cores of such showers contain very intense halos recorded on X-ray films.

These effects have to be produced by BARYONS that enter the detector. Multi-halo events should presumably be interpreted as involving multi-BARYON states, although the initial production of very energetic $W$’s and $Z$’s could also be involved. In the very highest energy events there could even be VECTOR MESON resonances.

Coplanarity of multi-halos.

The coplanarity of multi-halos in very high energy showers is a striking phenomenon having an established statistical significance. Results from the Pamir collaboration[21] are illustrated in Fig. 14. The X-rays for individual events are shown as well as the energy-dependence of the alignment. A table also illustrates how conventional models fail to produce the alignment. The experimenters emphasize that the total cross-section for halo events is far too large for them to originate from minijet configurations[22].

My description of the alignment phenomenon in diffractive production of BARYONS provides a direct explanation of this phenomenon. It is the same as is seen in the diffractive production of strange baryons at the ISR!

Large $p_\perp$ production of “Centauros” - with low electromagnetic energy, and “Chirons” - with apparent anomalously low $p_\perp$ in secondary showers.
Familiar plots of hadronic versus electromagnetic energy for Chacaltaya/Pamir\textsuperscript{16} data and the comparison with simulations are shown in Fig. 15. Centauro events represent the extreme of a general phenomenon that less electromagnetic energy is produced than in normal pion production events. The overall $p_{\perp}$ involved is apparently large but from their narrowness, the $p_{\perp}$ in secondary showers appears to be anomalously small. The general class of events with these $p_{\perp}$ properties are referred to as Chirons.

As we have said, BARYONS will generally be produced in the initial atmospheric collision of the Cosmic Ray primary. We can assume they will sometimes decay directly just above or in the detector. Often they will undergo secondary collisions and then decay similarly. The collisions and (or) the decay will involve very high initial $p_{\perp}$ and can take place sufficiently close to the detector that secondary $p_{\perp}$ within produced showers is normal even though they appear anomalously narrow. Since multiple $W$, $Z$ and $\eta_6$ intermediate states will again be involved, we can anticipate that in general the production of heavy flavors, taus and muons, will produce final states that will be interpreted as anomalously “hadron-rich” in the detector.

**Excess of (underground) muon pairs with large separation.**

The underground muon experiments also measure the distribution of the distance separation of muon pairs. The MACRO distributions\textsuperscript{23} are shown in Fig. 16. There is an apparent excess at large distances which would not be expected from conventional physics models. Not surprisingly, I would like to interpret the excess as evidence that $Z^0$'s are being directly produced, with a hadronic cross-section, in high-energy Cosmic Rays. Potentially $Z^0$ events could be explicitly identified. This could provide, strong, direct evidence for new physics such as I am proposing.

**Large zenith angle excess of high-energy air showers and azimuthal asymmetry in $\gamma$ and hadron family production.**

Finally I come to some further results from the HADRON experiment. Fig. 17 shows\textsuperscript{24} the zenith angle dependence for high-energy showers at two energies. The straight lines are conventional physics simulations at the two energies. There is a clear excess at large zenith angle at the highest energy. Also shown, in Fig. 17(b), is the zenith angle dependence of a break in the general size (energy) spectra of the showers. It is interesting that the break is essentially independent of the zenith angle and is located at the energy of the knee, in the conventionally induced primary energy spectrum. Since showers at different angles degrade differently in the atmosphere this, in itself, suggests that there is some physics effect in the break which is not simply related to the primary spectrum. Indeed it clearly leads to the
suggestion\cite{1,24}, referred to in the Introduction, that there is a “new physics” effect involved in the knee, and not just a simple change in spectrum.

In Fig. 18 we show the most exotic (and, if it should be confirmed, perhaps the most exciting) result from the HADRON experiment. A striking asymmetry in the azimuthal angular dependence\cite{25} of the large zenith angle showers is shown. This could perhaps be explained\cite{25} as due to the earth’s magnetic field if massive, negatively charged, particles are preferentially responsible for the showers.

I interpret these last results as evidence that in initial atmospheric collisions secondary, semi-stable, very energetic, particles are produced at varying (relatively) large angle, which are then interpreted as (separated) large zenith angle primary showers. If such secondary particles are responsible for the excess, this could explain why the spectrum break is at the same shower size independently of the zenith angle. My proposal is, of course, that the secondary particles are BARYONS. According to our diffractive production argument above, the larger angle BARYONS contributing to the larger zenith angle showers will be preferentially negatively charged.

It seems possible therefore that the azimuthal asymmetry could be explained by the charge asymmetry of the larger angle versus forward angle diffractive production of BARYON pairs described in the last Section.

7. NEW HARD SCATTERING PROCESSES AND TOP PRODUCTION.

If the new physics seen in Cosmic Rays were simply diffractive production of $W$ and $Z$ pairs (or perhaps $\eta_6$ pairs) then we might estimate the effective threshold to be, say, $x = (1 - M^2/s) \geq 0.96$ i.e.

$$\sqrt{s} \geq 5 \ M \ \sim \ 5 \times 160 \ GeV$$
$$\sim \ 800 \ GeV$$

and so to be visible at the Fermilab Tevatron. Indeed, it remains possible that $W$ pairs are produced, in some number, relatively far forward since this would be impossible to determine with the present detectors.

From our discussion in previous sections it is clear that the more distinctive effects involve at least BARYON pair production. The corresponding diffractive threshold would then be roughly

$$\sqrt{s} \geq 5 \ M \ \sim \ 5 \times 800 \ GeV$$
$$\sim \ 4 \ TeV$$

which is consistent with the Cosmic Ray effects. Of course, we can also expect some effects of the new sector to show up at energies well below the diffractive threshold.
Indeed we might expect the new quark sector to first show up in the highest transverse energy (but very rare) hard scattering events. Instanton interactions will provide transitions from the (light) triplet quark sector, to the sextet sector. Amongst the simplest possible states that can be produced are $W^+W^-$, $Z^0Z^0$, $\eta\eta$, $Z^0\gamma$ and $\gamma\gamma$. There were indications from UA1\textsuperscript{26} that the hard scattering cross-section for $W$ pairs is indeed anomalously large. The events at CERN were detected in the $WW \rightarrow$ leptons + 2 jet channel, which, of course, has a relatively large branching ratio. However, at the Tevatron this channel may be obscured since the background from conventional QCD processes is much larger than at the CERN collider. Nevertheless an excess of very high energy hard scattering events may be accumulating at the Tevatron (including $Z^0\gamma$ and $\gamma\gamma$ events). Although these events are not yet statistically significant, they may become so as the experiments continue to take data.

Enhanced electroweak scale instanton interactions can provide transitions from the familiar (light) triplet quark sector, not only to the sextet sector we have been discussing, but also to states that are a combination of sextet and (preferentially) heavy triplet quarks, and even to purely triplet heavy quark states. This implies that the top quark (with a mass of $\sim 170$ Gev according to recent CDF results\textsuperscript{27}) may have a larger production cross-section than standard perturbative estimates would give. Additional states that can be produced include

\[ W^+W^- + b\bar{b}, \quad Z^0Z^0 + b\bar{b}, \quad ... \]

The first state can clearly be directly confused with top production. Indeed in the CDF analysis\textsuperscript{27} searching for candidate top events, a few events have been found which are candidates to be identified with the second final state. In many respects, these events strongly resemble those identified as top events, but they should not be present at all according to the Standard Model. This clearly suggests that some of the candidate top events might in fact be direct $WW + b\bar{b}$ events. CDF also has a clear $WZ$ event which has a very low probability to occur, according to the Standard Model. An instanton interaction has to conserve charge in the sextet sector but could produce a $WWZ$ state, with one $W$ in a region of phase space where it escapes detection.

We conclude that a glimpse of sextet quark physics at the Tevatron collider may have already been provided. As data is accumulated it should become clear whether this is indeed the case. If it is, there will be a lot more than top quark production that provides “new physics” in the highest-energy hard scattering events.
References

[1] S. I. Nikolsky, *XXIII ICRC, Calgary*, 4, 243 (1993), S. B. Shaulov, *VII International Symposium on Very High Energy Cosmic Ray Interactions, Michigan*, 94 (1992).

[2] A. R. White, *Int. J. Mod. Phys.* A8, 4755 (1993).

[3] A. R. White, *Int. J. Mod. Phys.* A6, 1859 (1991).

[4] A. A. Migdal, A. M. Polyakov and K. A. Ter-Martirosyan, *Zh. Eksp. Teor. Fiz.* 67, 84 (1974); H. D. I. Abarbanel and J. B. Bronzan, *Phys. Rev.* D9, 2397 (1974).

[5] T. Gaisser and C-I. Tan, *Phys. Rev.* D8, 3881 (1973); J. W. Dash, E. Manesis and S. T. Jones, *Phys. Rev.* D18, 303 (1978).

[6] T. Banks and A. Zaks, *Nucl. Phys.* B196, 189 (1982).

[7] D. J. Gross and F. Wilczek, *Phys. Rev.* D8, 3633 (1973).

[8] W. J. Marciano, *Phys. Rev.* D21, 2425 (1980); E. Braaten, A. R. White and C. R. Willcox, *Int. J. Mod. Phys.* A1 693 (1986).

[9] K. Kang and A. R. White, *Int. J. Mod. Phys.* A2, 409 (1987).

[10] K. Kang, I. G. Knowles and A. R. White, *Mod. Phys. Letts.* A8, 1611 (1993).

[11] A. R. White, ANL-HEP-CP-93-56 (1993).

[12] S. Weinberg, *Phys. Rev. Lett.* 40, 223 (1978); F. Wilczek, *Phys. Rev. Lett.* 40, 279 (1978).

[13] R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* 38, 1440 (1977).

[14] A. H. Mueller, *Nucl. Phys.* B250, 327 (1985); C. N. Lovett-Turner and C. J. Maxwell, Durham Preprint, DTP/94/58 (1994).

[15] R608 Collaboration, *Phys. Letts.* B163, 267 (1985).

[16] Chacaltaya and Pamir Collaboration, *Nucl. Phys.* B370, 365 (1992).

[17] U. Das Gupta et al., *Phys. Rev.* D45, 1459 (1992).

[18] The MACRO collaboration, *XXIII ICRC, Calgary*, 2, 97 (1993).

[19] T. Gaisser et al., *Phys. Rev.* D47, 1919 (1993), P. Sokolsky, Highlight talk, XXIII ICRC, Calgary (1993).
[20] Chacaltaya and Pamir Collaboration, *XXIII ICRC, Calgary*, 4, 116-139 (1993).

[21] S. A. Slavatinsky, *VII International Symposium on Very High Energy Cosmic Ray Interactions, Michigan*, 3 (1992).

[22] F. Halzen and D. A. Morris, *Phys. Rev.* D52, 1435 (1990).

[23] The MACRO collaboration, *XXIII ICRC, Calgary*, 2, 93 (1993).

[24] L. G. Dedenko and V. I. Yakovlev, *XXIII ICRC, Calgary*, 4, 387 (1993).

[25] K. V. Cherdyntseva et al., *XXIII ICRC, Calgary*, 4, 88 (1993).

[26] A. Bohrer - UA1 Collaboration, *Proceedings of the 8th Topical Workshop On Proton-Antiproton Collider Physics, Italy* (1989).

[27] CDF Collaboration, *Phys. Rev. Letts.* 73, 225 (1994), Fermilab Preprint FERMILAB-Pub-94/097-E (1994).
Figure Captions

Fig. 1 Multiperipheral pion production generating the Regge pole Pomeron.

Fig. 2 Varying multiplicity densities on the rapidity axis generate higher-order Pomeron diagrams.

Fig. 3 Evolution of the $\beta$-function with $N_f$ - (a) $N_f \sim 5, 6$ (b) $N_f \sim 14, 15$ (c) $N_f = 16$

Fig. 4 The Critical Pomeron asymptotic diffraction peak approaches a simple peak if quark masses are sent to zero.

Fig. 5 Instanton interactions combined with condensates generate multiple vertices for $W$’s, $Z$’s and $\eta_c$’s,

Fig. 7 Coplanar diffractive production of strange baryons in experiment R608 at the ISR.

Fig. 8 Relation between the the family flux and power indices of the energy spectrum $\beta$ (a) for single core showers and (b) for shower clusters, in the energy range of 10-50 TeV, for the joint (J), Pamir (P) and Chacaltaya (C) chambers, compared to simulation models. (b) The single-core comparison when a heavy primary composition is used in the models.

Fig 9 (a) Energy spectra of $\gamma$-quanta and electrons in EAS cores with varying primary energies. The wide shaded strip is a simulation with primary protons, the narrow strip is with a heavy nuclei composition. (b) The experimental muon multiplicity distribution compared to simulations with 1) heavy nuclei primary composition 2) an increasing inelasticity coefficient and 3) the energy of the fragmentation region is lost from the hadron-electron cascades.

Fig. 10 (a) The underground muon multiplicity distribution results from the MACRO experiment. (b) The relationship between muon multiplicities and primary energy in conventional physics simulation models.

Fig. 11 Average $X_{max}$ as a function of primary energy. Black dots : data. Open squares : simulation with a proton dominant primary composition. Open circles : simulation with a dominant heavy nuclei composition. Diamonds : simulation with an energy-dependent composition.

Fig. 12 (a) Distribution of shower starting position for Chiron-type families observed by Chacaltaya two-storey chambers. The dotted line represents exponential decrease with the geometrical attenuation mean free path. (b) The $\Delta T$ distribution of 170 hadrons with $E_\gamma \geq 10$ TeV in 16 high energy families with $E_{family} \geq 700$ TeV observed in the thick
lead chambers of the Pamir experiment. (c) For comparison the $\Delta T$ distribution of all hadrons in the Pamir lead chamber.

Fig. 13 (a) Shower transitions with spot darkness plotted against depth for two events in the Pamir lead chambers (b) Examples of strongly penetrating, small spread, shower clusters in Chacaltaya chambers.

Fig. 14 a) Darkness contours on X-ray films for 6 Pamir multicore halo events. b) The energy dependence of the percentage of four-core events satisfying $\lambda_4 \geq 0.8$ where $\lambda_4$ is a suitably defined alignment parameter. c) Table comparing alignment percentages for simulations and experimental data.

Fig. 15 (a) The upper graph is a scatter plot of the number of hadrons, $N_h(E_h^{(\gamma)} \geq 4$ TeV) in a family and the fraction of the family energy carried by hadrons $Q_h (\equiv \sum E_h^{(\gamma)}/\sum E_{(\gamma)} + E_h^{(\gamma)})$. Closed circles are for 173 families in the joint chambers and 135 families in the Pamir chambers, and open circles are for 121 families in the Chacaltaya chambers. The lower graph is a simulation. The primary composition assumed is - solid black dot = proton, open dot = alpha, diamond = CNO, x = heavy, + = iron. (b) Is the same as (a) but with the families selected to have lateral spread $\langle E^*R^* \rangle < 300$ GeV.m.

Fig. 16 The MACRO distance separation for muon pairs compared with simulations (a) for muon pairs within all muon events (b) for dimuon events only.
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