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THE η_6 AT LEP AND TRISTAN.

Kyungsik Kang

Physics Department

Brown University

Providence, RI 02912

Ian G. Knowles and Alan R. White

High Energy Physics Division

Argonne National Laboratory

Argonne, IL 60439

Abstract

The η_6 is a "heavy axion" remnant of dynamical electroweak symmetry breaking by a color sextet quark condensate. Electroweak scale color instanton interactions allow it to be both very massive and yet be responsible for Strong CP conservation in the color triplet quark sector. It may have been seen at LEP via its two-photon decay mode and at TRISTAN via its hadronic decay modes.

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Electroweak dynamical symmetry breaking by a chiral condensate of color sextet quarks[1] has many theoretically attractive features, including the special resolution of the Strong CP problem via a heavy axion that we outline below. However, it should also be emphasised that if this should turn out to be the path chosen by nature it provides a particularly inviting prospect for experimental high-energy physics. Because of the direct coupling of the strong and electroweak interaction, the spectrum of new phenomena that can be expected to appear, at both currently operating accelerators and the future LHC and SSC machines, is probably at least as large, if not considerably larger, than in any other symmetry-breaking scenario.

The purpose of this paper is to focus on the tantalizing possibility that a distinctive feature of the symmetry breaking, namely the “heavy axion” η_6 , has already been seen experimentally. This particle is expected to have both a major two-photon decay mode and characteristic high multiplicity hadron decays. It is therefore an excellent candidate for the new particle, with a mass of 59 GeV, suggested by the two-photon pairs seen at LEP[2]. That a small bump is also seen[3] at TRISTAN, at just this energy, can then be interpreted as due to its hadronic decay modes.

We expect the strong interaction dynamics of the sextet quark sector of QCD to be very different from that of the triplet sector. In particular we anticipate that relatively complicated instanton generated interactions (at and above the electroweak scale), which include “Strong” CP -violating effects, will play an important role[4, 5]. As a result, only a minimal amount of rescaling of physics from the triplet to the sextet sector will be possible. We will (if candidate sextet phenomena begin to appear) be studying a new realm of gauge theory physics and it will not be surprising if, to a large extent, the theory has to follow along semi-phenomenologically behind the experimental discoveries.

Although it is correctly described as a heavy axion, the η_6 is the “Higgs particle” of sextet symmetry breaking in the sense that its experimental discovery would be the most immediate confirmation of this form of symmetry breaking. Motivated, in part, by the anomalous real part measured in elastic $\bar{p}p$ scattering at the apparent threshold energy[6], we suggested[7] that the η_6 be identified with a very heavy state, with a mass[8] of $O(60)$ GeV, seen in exotic Cosmic ray events[9]. Because of the axion nature of the η_6 , we proposed that this particle be looked for in accelerators via its two-photon decay mode.

As is by now well known[2], the L3, DELPHI, and ALEPH experiments at LEP have

recently reported several events of the form $Z^0 \rightarrow l^+ l^- + \gamma\gamma$, in which the mass of the $\gamma\gamma$ pair is $O(60)$ GeV. The lepton pairs are either muons or electrons and we have separately plotted the $m_{\gamma\gamma}$ distribution for muon and electron pairs in Fig. 1. There are as yet, no neutrino or τ pairs, although DELPHI has one candidate quark pair event. While the kinematics of some of the events may be compatible with QED radiation, others look implausible explained this way. In particular the muon events in the 59 GeV bin are all “large angle” events and do not look like naive radiative events. Rather they suggest the existence of a new “particle”, i.e. resonance, with a mass of 59 GeV and a width of (up to) $O(1)$ GeV. Clearly a case could be made from Fig. 1 that *only the muon pair events* suggest a new resonance. (Particularly since the two electron events close to 59 GeV are both good candidates for QED radiation.) This is potentially a significant feature, as we shall see.

Since we expect the η_6 to have hadronic decay modes involving relatively complicated high multiplicity states, it is particularly interesting that the new “particle” may also have been seen at TRISTAN. In fact all three experiments saw[3] a small peak in the hadronic cross-section at 59.05 GeV. An error-weighted average of the TRISTAN results for R is shown in Fig. 2. AMY actually obtained a value more than 30% above the standard model value (although with a large error - giving at most a “ 2σ effect”). If this effect is produced by the same new particle that appears in the LEP events, we can infer both that it couples to electrons and that it does indeed have *major hadronic decay modes*. If this particle had direct electroweak couplings to quark and lepton states in analogy, say, with the Z^0 , then the corresponding decays would surely have already been seen at LEP. It seems more likely to us that the width is produced mostly by the photon pairs and high multiplicity hadron states which would not be so easily identified at LEP, but clearly would be registered at TRISTAN.

We can briefly summarise the essentials of sextet symmetry breaking[1] as follows. 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*. Within QCD , conventional chiral dynamics will break the sextet axial flavor symmetries spontaneously and produce four massless pseudoscalar mesons (Goldstone bosons), which we denote as π_6^+ , π_6^- , π_6^0 and η_6 . The π_6^+ , π_6^- , and π_6^0 are “eaten” by the massless electroweak gauge bosons and respectively become the third components of the massive W^+ , W^- and Z^0 - giving $M_W \sim g F_{\pi_6}$ where F_{π_6} is a QCD

scale. $F_{\pi_6} \sim 250 \text{ GeV}$ is consistent with an elementary “Casimir Scaling” rule[1].

The η_6 is not involved in generating mass for the electroweak gauge bosons and remains a Goldstone boson. A first assumption might be that the η_6 somehow acquires an electroweak scale mass which is nevertheless small enough that we can utilise *PCAC* for the sextet $U(1)$ axial current. The analog of the familiar $\pi^0 \rightarrow 2\gamma$ calculation, but involving the sextet quark triangle anomaly, will give amplitudes for

$$\eta_6 \rightarrow \gamma\gamma, \quad Z^0 \rightarrow \eta_6 + \gamma \quad \text{and} \quad Z^0 \rightarrow \eta_6 + Z^{0*}. \quad (1)$$

where the Z^{0*} is an off-shell Z^0 .

Note that if the η_6 is a pseudoscalar, and *CP* is conserved, the existence of just two independent momenta implies that each of the vertices in (1) must have the “pseudotensor” kinematic form

$$\Gamma_{\mu\nu} = C(p, q) \epsilon_{\mu\nu\gamma\delta} p^\gamma q^\delta \quad (2)$$

where p and q are the momenta involved, and $C(p, q)$ can be calculated from the anomaly. Assuming a mass of 60 GeV, gives[10] a very narrow width of 0.17 keV for $\eta_6 \rightarrow \gamma\gamma$. For $Z^0 \rightarrow \eta_6 + \gamma$ the anomaly calculation[11] predicts one event in 20 million at LEP, while from the $Z^0 \rightarrow \eta_6 + Z^{0*}$ calculation we obtain a rate for $Z^0 \rightarrow \eta_6 + Z^{0*} \rightarrow \eta_6 + \mu^+ \mu^-$ of 2 events in a billion. This is at least three orders of magnitude too small to explain the two photon events. We conclude that, in general, the anomaly gives a set of amplitudes which are far too small to be compatible with the LEP events.

The sextet quark anomaly estimates for amplitudes can only be significantly wrong if Goldstone boson intermediate states can contribute to the processes involved. At this point the special “heavy axion” nature of the η_6 becomes crucial. Apart from its high mass, the η_6 is actually a “Peccei-Quinn axion” and can be responsible for Strong *CP* conservation in the triplet quark sector in a conventional manner[12]. However, if the η_6 is the origin of *CP* conservation in the triplet sector, then the sextet sector (and sextet Goldstone boson amplitudes in particular) will not be *CP* conserving. As a result, there will be intermediate states contributing to “longitudinal” Z^0 and $W^\pm$ amplitudes involving the η_6 which do invalidate the anomaly estimates, and could give large enough cross-sections at LEP and TRISTAN. We can briefly summarise the physics behind the *CP*-related properties of the η_6 as follows.

The Peccei-Quinn argument for Strong *CP* conservation requires[12] the existence of

a Goldstone Boson axion a that couples to the QCD color anomaly and gives an effective lagrangian for the triplet quark sector of the form

$$\mathcal{L} = \mathcal{L}_{QCD} + \tilde{\theta} \frac{g^2}{32\pi^2} F\tilde{F} + \frac{a}{v_{PQ}} \frac{g^2}{32\pi^2} F\tilde{F} + \dots \quad (3)$$

where $\mathcal{L}_{QCD}$ is the usual QCD lagrangian for the gauge and triplet quark sectors and, in a conventional notation, $\tilde{\theta} = \theta + \arg \det m_3$, where m_3 is the triplet quark mass matrix. v_{PQ} is the vacuum condensate which produces the Goldstone Boson axion a . An appropriate shift in a will absorb the CP -violating $\tilde{\theta}$ term and a sufficient condition for the minimum of the axion potential to occur at $\hat{\theta} = 0$ (where now $\hat{\theta} = \theta + \arg \det m_3 + \langle a \rangle / v_{PQ}$) is that $\langle F\tilde{F} \rangle$ vanishes like $\sin \hat{\theta}$ at $\hat{\theta} = 0$. This is expected to be the case for normal instanton interactions. A mass for the axion is generated by the curvature of the potential at the minimum. If all of the relevant QCD dynamics involves only the normal QCD scale Λ_{QCD} , this mass is inevitably of $O(\Lambda_{QCD}^2/v_{PQ})$ and hence very small[12].

If we identify a with the η_6 , the mass can be much higher just because of the intricate QCD dynamics at the sextet scale. To generate the usual quark and lepton masses it is necessary to add four-fermion couplings to the theory which combine appropriately with the $\langle \bar{Q}Q \rangle$ sextet condensate. If we then obtain (3) by integrating out the sextet quark sector, we must include η_6 vertices induced[5] by the combination of $\bar{Q}Q\bar{q}q$ vertices, the $\langle \bar{Q}Q \rangle$ condensate, and instanton interactions involving sextet quarks. The instanton interactions are actually *very high order fermion vertices*. The simplest such vertex involves each flavor of triplet quark (and antiquark) and *five* of each flavor of sextet quark (and anti-quark). When the condensate and four-fermion vertices are combined with the instanton vertices, a large array of interactions is obtained. (Indeed the resulting low order vertices may be enhanced by large factorial factors associated with the possibilities for pair condensation.) These fermion vertices can then be coupled by arbitrarily complicated gluon interactions - which are effectively infra-red interactions at the sextet scale.

Note that with the additional two flavors of sextet quarks, the resulting evolution of α_s is negligible above the electroweak (sextet) scale. Indeed there is an effective *infra-red* fixed-point controlling the dynamics of the sextet QCD sector[4]. The associated absence of the infra-red growth of the gauge coupling implies that, in this sector, confinement and

chiral symmetry breaking will involve the instanton interactions we are discussing as an important “infra-red” effect. (There are no infra-red renormalons[4] and so instantons don’t melt!). For our present purposes all that we need extract from this complicated dynamical situation is that the sextet instanton interactions generating η_6 vertices all contain a factor[5] of $\cos[\tilde{\theta} + \langle \eta_6 \rangle]$. Therefore an axion potential of the form $V(\cos[\tilde{\theta} + \langle \eta_6 \rangle])$ is generated. Such a potential will naturally retain the CP -conserving minimum at $\tilde{\theta} + \langle \eta_6 \rangle = 0$ while also giving an η_6 mass (the curvature at the minimum) of order the electroweak scale - say 60 GeV!

Focussing now on the CP properties of the sextet sector, we note that the Peccei-Quinn argument is inapplicable since we can not write a lagrangian of the form (3) - that is involving both the η_6 and the gluon field - to describe sextet quark interactions. If the gluon field is to be present, then we must use the full QCD lagrangian, written in terms of elementary fields, for the combined triplet and sextet sectors. This clearly has no axion. Also, we know that the four-fermion $\bar{Q}Q\bar{q}q$ couplings that we add to the theory must be CP -violating since they have to produce the CP -violating triplet quark mass matrix. Because there is *no axion*, the induced fermion vertices involving instanton interactions will automatically be CP (and separately C) -violating. In effect, a consequence of the usual CP violation in the triplet quark masses is that the “low-energy” effective lagrangian for QCD interactions of the η_6 , π_6^+ , π_6^- , and π_6^0 is necessarily CP -violating. In unitary gauge, it is the “longitudinal” (or scalar) components of the gauge boson fields, i.e. $\partial^\mu Z_\mu^0$, $\partial^\mu W_\mu^+$ and $\partial^\mu W_\mu^-$, that inherit the interactions of the Goldstone bosons π_6^0 , π_6^+ and π_6^- respectively[13]. Therefore such interactions may give large, CP -violating, couplings of the form $\eta_6 \partial^\mu Z_\mu^0 \partial^\mu Z_\mu^0$, $\eta_6 \partial^\mu W_\mu^+ \partial^\mu W_\mu^-$, $\eta_6 \partial^\mu Z_\mu^0 \partial^\mu W_\mu^+ \partial^\mu W_\mu^-$... etc.. We consider now how these couplings can contribute to processes at LEP and TRISTAN involving the η_6 .

An essential first step is to write an effective lagrangian for the strong (unitary gauge) longitudinal amplitudes. This will be quite different from conventional chiral lagrangians because of the CP violating amplitudes. Indeed these amplitudes are all zero in the exact chiral limit (that is in the absence of four-fermion $\bar{Q}Q\bar{q}q$ couplings) and so we shall assume they are not constrained by PCAC etc.. From our present perspective, they are simply parameters that should, presumably, be of comparable order of magnitude. We can then add the electroweak interaction and, in first approximation, compute to lowest order in the

electroweak couplings. For the moment we use this procedure only implicitly to obtain some order of magnitude estimates. We shall initially assume that, unless we argue otherwise, all momentum and mass factors are $O(M_{Z^0})$ and effectively cancel in dimensionless quantities. Therefore only the magnitude of electroweak couplings, small to large mass ratios, and the order of magnitude of sextet couplings will appear in our estimates.

First we note that, as illustrated in Fig. 3, $\eta_6 \rightarrow \gamma\gamma$ is given by a $\partial^\mu W_\mu$ loop which, because of the unitary gauge propagators, is clearly dominated by momenta $O(M_{Z^0})$. If we denote the $\eta_6 \partial^\mu W_\mu^+ \partial^\mu W_\mu^-$ vertex by V_1 and the full η_6 width by Γ_{η_6} , we obtain a branching ratio

$$B_{\eta_6 \rightarrow \gamma\gamma} \sim \alpha_{EM}^2 V_1^2 / m_{\eta_6} \Gamma_{\eta_6} \quad \rightarrow \quad V_1 \sim 10^3 \sqrt{\Gamma_{\eta_6 \rightarrow \gamma\gamma}} \quad (4)$$

If (as we shall give arguments for below) this ratio $\sim 10^{-1}$, and we assume $\Gamma_{\eta_6} \lesssim 1$ GeV, (4) implies that V_1 is $O(1-10)$ on the electroweak scale.

There are contributions to $\eta_6 \rightarrow l^+ l^-$ from similar loops to that of Fig. 3 involving longitudinal W 's or Z^0 's but with one boson propagator replaced by a lepton propagator. These amplitudes should therefore be smaller by $O(1/M_W)$. In fact, to produce the scalar combination of helicities, the amplitudes must involve m_l and are actually $O(m_l/M_W) \sim 10^{-5}$ for an electron pair. This gives too small a coupling to allow the η_6 to be seen at TRISTAN. A larger amplitude is obtained by producing two photons via Fig. 3 which scatter electromagnetically into a lepton pair, via lepton exchange. (The infra-red behavior of the photon propagators prevents the process from vanishing as the electron mass goes to zero and so gives an $O(\alpha_{EM})$ amplitude rather than $O(m_e/M_{Z^0})$ [14]). The resulting coupling gives a cross-section

$$\sigma(e^+ e^- \rightarrow \text{hadrons}) \sim B_{\eta_6 \rightarrow \gamma\gamma} \alpha_{EM}^2 \quad (5)$$

$\sim 10\%$ of the total hadronic cross-section at TRISTAN (assuming again that $\Gamma_{\eta_6} \lesssim 1$ GeV). This is not a major effect but it is the right order of magnitude to be compatible with the data shown in Fig. 2 and provides one argument why the two photon branching ratio of the η_6 should be $\sim 10\%$. However, the error bars on the data would clearly have to be significantly improved to determine that the effect was definitively present.

In general photon emission will be strongly favored over leptons because of the direct coupling of the photon to sextet Goldstone bosons at large momentum. Indeed if CP and C are not conserved, as we are assuming, then after two photon decay, the three photon mode

could be the next most important electroweak decay for the η_6 .

Consider next the hadronic decay modes of the η_6 . We anticipate that perturbative gluon emission automatically exposes the large sextet quark constituent mass (which is presumably $\sim 300 - 400$ GeV) and so is very suppressed. Instead we expect instanton interactions to provide the major communication between the sextet and triplet sectors. The simplest possible final state for a decay of the η_6 mediated by an instanton interaction would be an isotropic distribution of five quarks and five antiquarks (one of each flavor), giving a high multiplicity hadron state with many (mini-)jets. (There is some suggestion in the data[15] that the increased cross-section at TRISTAN is in the higher multiplicities). At LEP, the combination of such a state with a hard lepton pair (i.e. $m_{l+l-} \sim 20 - 30$ GeV as in the two photon events) could be looked for and some examples should be isolatable if there are indeed a substantial number of such events.

At present we have no way of estimating the ratio of hadronic to two photon branching ratios theoretically. Another phenomenological estimate, which is clearly independent of that based on TRISTAN data, is obtained by appealing to our suggestion[7] that hadronic diffractive production of the η_6 is responsible for Geminion and Mini-Centauro Cosmic ray events[9], and is also responsible (via a threshold effect) for an anomalous contribution to the real part of the hadron elastic scattering amplitude[6]. The number of Geminion events thought to be associated with a 60 GeV state, suggests a two photon cross-section of $O(100-500) \mu\text{bs.}$, while the Mini-Centauros and the threshold effect suggest a hadronic cross-section $O(2-8) \text{ mbs.}$ Again we conclude that the two photon branching ratio should be $\sim 10\%$.

If the LEP events are indeed produced by $Z^0 \rightarrow \eta_6 + Z^{0*} \rightarrow [\gamma\gamma] + [l^+l^-]$ and CP is not conserved, we can add an additional tensor vertex to (2) of the form

$$V_{\mu\nu} = \left[(p \cdot q)q_\mu - q^2 p_\mu \right] \left[T(p, q)[(q \cdot p)p_\nu - p^2 q_\nu] + L(p, q)[q^2 p_\nu] \right] \quad (6)$$

where now p is the momentum of the Z^{0*} , so that T and L are respectively invariant "transverse" and "longitudinal" amplitudes. From the above discussion we may assume that L contains a large $Z^0 \rightarrow \partial^\mu Z_\mu^0 + \eta_6$ coupling (which could again be thought of as proceeding via a $\partial^\mu W_\mu$ loop).

There is an electroweak coupling of the initial transverse Z^0 involved in L and so we will estimate it as $O(gV_2)$, where g is the $SU(2)$ gauge coupling and V_2 is a (potentially

large) pure sextet QCD amplitude. We note, however, that the longitudinal component of a Z^0 propagator coupled to a lepton pair reduces to

$$\bar{u}(k) \frac{\not{p}}{M_{Z^0}^2} [v_l - a_l \gamma_5] v(p-k) = -2 \frac{m_l}{M_{Z^0}^2} a_l \bar{u} \gamma_5 v \quad (7)$$

where m_l is the lepton mass and u and v are lepton spinors. v_l and a_l are the vector and axial Z^0 couplings to the lepton pair. The suppression factor (m_l/M_{Z^0}) implies there will be *no neutrino pairs*, a negligible number of electron pairs, and, at first sight, an overwhelming number of tau pairs compared to muon pairs!

Using $\alpha_W (= g^2/4\pi) \sim 1/30$, we estimate the branching ratio for $Z^0 \rightarrow 2\gamma + \mu^+ \mu^-$ as

$$\sim V_2^2 \alpha_W^2 (m_\mu/M_{Z^0})^2 10^{-1}/M_{Z^0} \Gamma_{Z^0} \sim V_2^2 10^{-12} \rightarrow V_2 \sim 10^3 \text{ GeV} \quad (8)$$

- if (for our present purposes) we take the width of the Z^0 to be $O(1)$ GeV and we estimate the LEP branching ratio to be $\sim 10^{-6}$. Clearly (8) is nicely consistent with (4) in giving the order of magnitude of the QCD sextet quark interaction.

While the predicted absence of electron pairs is, perhaps, consistent with the experimental situation the big question is now why there are not ~ 300 tau pairs for every muon pair? A perturbative correction to the tree amplitude for tau pairs would be the loop diagram shown in Fig. 4, involving another sextet pion vertex - V_3 . Given that V_3 is CP -violating (and therefore complex) we obtain a potentially negative amplitude if we take the internal lepton line on-shell. Since this amplitude is then $O(m_\tau^2)$ we might suppose it to be small. However, if Q is the resulting average momentum in the loop (after the lepton line is taken on-shell) we estimate that there is an effective perturbative expansion parameter

$$\sim g V_3 m_\tau / M_{Z^0} Q \sim 1 \quad (9)$$

if we take $Q \sim 10 \text{ GeV}$, and assume that V_3 is of the same order of magnitude as V_1 and V_2 . So the effective perturbation parameter involves the lepton mass directly and for tau pairs is sufficiently large that the expansion breaks down. Therefore the tau pair amplitude could well not be larger than the muon pair amplitude.

We must also discuss the production of light mass quark pairs by the Z^{0*} . If we carry over the above analysis of leptons directly to quarks, we would conclude that only the strange quark (with a mass of the same order of magnitude as the muon) gives an observable

cross-section which can be reliably estimated perturbatively. However, since quark pairs carry color, they will also interact with the initial sextet quark vertex, via QCD , and for this reason alone, the amplitude can not be evaluated perturbatively. Therefore, although we can not calculate the amplitudes, there is no immediate conflict in the relative lack of quark (or tau) pairs.

Note that there may be a further source of lepton pairs accompanying η_6 production. Four-fermion sextet/lepton couplings could provide a direct (short-distance) coupling of lepton pairs into electroweak scale instanton interactions - without going via the electroweak interaction - and give direct $Z^0 \rightarrow \eta_6 + l^+l^-$ vertices. If CP is conserved, these amplitudes can not be large. If CP is not conserved, there could be couplings that are independent of the mass generation mechanism (involving right-handed leptons and sextet quarks) which give large amplitudes. There are strong constraints on such couplings which we shall not elaborate on here. We note only that they could ultimately turn out to be necessary to understand tau pair amplitudes. They would certainly have to play a major role if muon pairs do not dominate over electron pairs in two photon events at LEP that are to be explained in terms of the η_6 .

In conclusion we can say that, at the order of magnitude level, a consistent picture of the properties of the η_6 has emerged which implies that it may indeed have been seen at both LEP and TRISTAN.

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Figure Captions

Fig. 1 The two photon mass distribution for the LEP events[2]. The bins used are 1 GeV wide and centered on the integer values. The errors vary from experiment to experiment but are not too different from the 0.5 GeV that our plot implies.

Fig. 2 The error-weighted average of data from TRISTAN[3] compared with a Standard Model prediction.

Fig. 3 The longitudinal W loop giving the two photon decay of the η_c .

Fig. 4 A one-loop correction to the τ -pair amplitude.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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