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# Theoretical implications of the resonance anomalies in the $e^+$-$e^-$ system*

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The phenomenological properties of the recent resonance anomalies at 3.1 GeV and 3.7 GeV in $e^+$-$e^-$ systems are confronted in a fairly systematic way with models presently known to us. These include charm-related models, neutral-intermediate-boson-type hypotheses, gauge-related models, and exotic suggestions that the resonant states may have abnormal $C$ parity or that the electromagnetic current has a color triplet piece. We conclude that none of the schemes proposed represents a really satisfactory interpretation of the data.

Recently, evidence has been found of an exceptionally narrow-width boson in $e^+e^-$ production[1] and in $e^+e^-$ annihilation[2] of unusually high mass 3.105 GeV. The particle has been named respectively the $J$ particle or the $\psi$ particle by their experimental discoverers; here we shall call the particle $X$ to steer clear of the nomenclature controversy. Further evidence of narrow peaks at 3.7 GeV (see Ref. 3) and perhaps also at higher masses 4.2 and 5.5 GeV have been suggested.

Before confronting these anomalies with theoretical models proposed to date, we need to discuss the necessary (theory-independent) phenomenology as a preliminary. The quoted width of the SLAC-LBL data[2] for the $X(3.105)$ is $\Gamma \leq 1.9$ MeV (FWHM) corresponding to the machine resolution, while the cross section for hadron production at the peak of the resonance is $2300 \pm 200$ nb, an enhancement of about 100 times the cross section outside the resonance. The second particle $X(3.695)$ is reported[3] to have $\Gamma_{\text{FWHM}} < 2.7$ MeV (the machine resolution) and peak cross section $> 500$ nb.

The mere *size* of the resonance cross section would suggest that the $s$-channel intermediary is either the *single-photon state* with angular momentum, parity, and charge-conjugation quantum numbers $J^{PC} = 1^{--}$ (which then also describes the quantum numbers of the $X$ particle) or a *single-boson intermediate state with roughly comparable coupling strength*. It appears reasonable to restrict the spin-parity possibilities for the boson intermediary to $J^P = 0^{\pm}$ and $J^P = 1^{\pm}$.

To estimate the leptonic width for $X$, we may employ the usual narrow-width formula

$$\int_{\text{peak}} \sigma(e^+e^- \to \text{hadrons})ds = \frac{4(2J+1)\pi^2}{m_X} \frac{\Gamma_{X\to l^+l^-}\Gamma_{X\to \text{hadrons}}}{\Gamma_{\text{total}}} \quad (l = e, \mu), \qquad (1)$$

where, if $\Gamma_{X\to\text{hadrons}} \sim \Gamma_{\text{total}}$, we have

$$\int_{\text{peak}} \sigma(e^+e^- \to \text{hadrons})ds \approx \frac{4(2J+1)\pi^2}{m_X}\Gamma_{X\to l^+l^-}. \qquad (2)$$

The hadronic width can then be determined from

$$\sigma_{X\to l\bar{l}}/\sigma_{X\to\text{hadrons}} = \Gamma_{X\to l\bar{l}}/\Gamma_{X\to\text{hadrons}}, \qquad (3)$$

where the left-hand side of (3) for $l = e$ is known experimentally.[2] Rough consistency with the SLAC-LBL data[2] is obtained for $J = 1$ by the following set of width values:

$$\Gamma_{X\to e\bar{e}} = \Gamma_{X\to\mu\bar{\mu}} \sim (4\text{–}5)\ \text{keV}, \quad \Gamma_{X\to\text{hadrons}}/\Gamma_{X\to l\bar{l}} \sim 20 \qquad (4)$$

for $X(3.105)$; comparable leptonic widths have also been reported for $X(3.695)$.[3] It is to be noted that for a given experimental cross section (assuming that it goes through one angular momentum channel), the maximum width $\Gamma_{\max}$ is obtained for $J = 0$. From Eqs. (1)–(3), and assuming that $\Gamma_{X\to e\bar{e}} = \Gamma_{X\to\mu\bar{\mu}}$, one might be tempted to conclude that[4]

$$\Gamma_{\max} < 330\ \text{keV}, \qquad (5)$$

*irrespective of spin*. The above estimates, however, ignore possible transverse polarization of the initial $e^+$-$e^-$ beam. It is easy to generalize the argument of Goldman and Vinciarelli[5] that the cross section $\sigma_J$ is independent of polarization of $e^+$-$e^-$ if the coupling is $\bar{e}(a + b\gamma_5)\gamma_\mu e J_\mu$ for arbitrary $a$ and $b$, i.e., for any arbitrary combination of vector and axial-vector boson exchange. The cross section $\sigma_J$ does depend on the initial polarization of $e^+$-$e^-$ in the form $\sigma_J \propto (1 \pm |P|^2)$ for $J = 0^{\mp}$; here $P$ denotes the (common) polarization coefficient of the beams. Hence Eq. (5) should be modified by the multiplicative factor $(1 \pm |P|^2)$ accordingly. The transverse polarization $P$ at the current SLAC-LBL-type energy appears, however, to build up very slowly.

Finally, it should be emphasized that the interference effect in $e^+e^- \to \mu^+\mu^-$ with background (together with the $1 + \cos^2\theta$ type angular distribution) in the neighborhood of the resonance peak would clearly establish the $1^-$ assignment over the $1^+$ axial-vector case.

We now proceed to catalog the various types of models proposed in the past which, to our knowledge, might have a bearing on the present anomaly.

### A. Charm related models

If $X$ is a charmed boson ($\bar{q}_C q$), where the charmed quantum number forbids its decay via strong and electromagnetic interactions [the GIM (Glashow-Iliopoulos-Maiani) class charmed particles[6] belong to this category], then there are substantial problems with the production mechanism in $e^+e^-$ via single-photon exchange since the photon is normally understood to be a charm singlet, hence $\gamma \not\rightarrow X$. Likewise, since $X$ now decays only via *weak* interactions, its decay width $\Gamma$ is likely to be of order $G_F^2 m_X^5 \sim 2\times 10^{-2}$ keV—which is far too small.

The Han-Nambu type charmed model[7] does allow for the possibility that charm is not conserved by electromagnetic nor weak interactions. Hence the $e^+e^- \rightarrow \gamma \rightarrow X$ chain is allowed, thus obviating the production difficulty encountered above. However, the typical $X$ decay will now involve a photon emitted together with other identified final-state particles[8] (perhaps compatible with the SLAC-LBL data where neutral particles in the final state are not always identified). The typical width $\Gamma_{X\rightarrow\gamma+h}$ (where $h$ denotes the inclusive hadron set of final states) is of order $\alpha m_X = 22$ MeV, which is too large to account for the $e^+e^-$ anomaly.[9]

Another possibility is to take the positronium analogy and consider the "charmonium" combination $X=(q_C\bar{q}_C)$. This has evidently no difficulties with production via single photon exchange since $X$ has 0 net charm quantum number. Though $X$ can now in principle decay to usual hadron final states via strong interactions, its decay width may be suppressed because of the coupling to charmed quarks, just as the decay of $\varphi(1.019)$ to ($\rho\pi$) is suppressed *vis-à-vis* ($K\bar{K}$) because it is assumed that the $\varphi(1.019)$ is coupled dominantly to the ($\lambda\bar{\lambda}$) quarks. A very detailed dynamical theory (e.g., asymptotic freedom) may be needed to understand why the strong decay width of $X(3.105)$ according to this picture can be of the order of 100 keV as indicated by Eq. (4). If we adopt the positronium analogy and identify $X = (q_C\bar{q}_C)$ with the $^3S_1$ state, then the $X$ can decay to the usual hadrons via three vector gluons intermediary (each gluon has $J^{PC}=1^{--}$). By suitably arranging the gluon–$X$-particle coupling to be sufficiently small (e.g., $g^2/4\pi \sim \frac{1}{10}$ in units where $e^2/4\pi = \alpha \simeq \frac{1}{137}$), one might *optimistically* hope to obtain the required hadronic width of $X(3.105)$ and the branching ratio

$$\Gamma_{X\rightarrow l\bar{l}}/\Gamma_{X\rightarrow \text{hadrons}} \sim \alpha^2/(g^2/4\pi)^3 \sim \tfrac{1}{10} \ .$$

The $^3S_1$ to $^1S_0$ level splitting ($\cong \frac{7}{12}\alpha^4 m_e$ for positronium in the ground state) would be about $(g^2/4\pi)^2$ in GeV units; hence the mass levels in this picture are likely to be rather closely spaced. It is entirely possible of course that the rather large mass splitting between $X(3.105)$ and $X(3.695)$ merely reflects that they correspond to the $^3S_1$ and $^3D_1$ states in the analogous ($q\bar{q}$) language; note that the splitting between $\rho(770)$ and $\rho'(1600)$ is roughly compatible with the splittings seen here. This would require a rather rich spectrum of expected states from ($q_C\bar{q}_C$), with $L$ excitation to be anticipated in the $e^+e^- \rightarrow$ hadrons system. *For a sufficiently rich spectrum of resonant states we cannot rule out the possibility that a new type of Dolen-Horn-Schmid duality[10] is in effect building up the $e^+e^- \rightarrow$ hadrons total cross section.*

### B. Intermediate-boson-related models

Here we concentrate on neutral-intermediate-boson type models not usually discussed in the context of gauge theories. This latter class will be discussed separately under (c) below.

The most elegant model of this type is that proposed recently by Sakurai[11] which attempts to relate the intermediate boson $X^0(3.105)$ with his earlier fermion-current model of neutral currents.[12] The agreement is satisfactory except, as he points out, that a boson mass as low as 3.1 GeV would require a fairly substantial variation in the inclusive neutral-current-to-charged-current ratio as we go from CERN energies to Fermilab energies. Typically,

$$d\sigma^{\nu N\rightarrow\nu+h}/dQ^2 \sim (d\sigma^{\nu N\rightarrow\nu+h}/dQ^2)_{m_X\rightarrow\infty}\frac{1}{(Q^2+m_X{}^2)^2} \ .$$

Hence for moderate values of $m_X$ and $Q^2$ *large*, there should be a fairly large attenuation of the inclusive neutral-current cross section. Furthermore, Adler[13] has pointed out that a dispersion-theoretic calculation of weak pion production (with nuclear-target charge-exchange corrections) shows that a neutral current with strength roughly comparable to the *isoscalar* electromagnetic current would produce a neutral-to-charged current $\pi^0$ production ratio[14] $R'({}_{13}\mathrm{Al}^{27}) \approx 0.001$, as compared with the value $\approx 0.17$ seen experimentally.[15]

Various forms of $B^0$ intermediate bosons have been proposed to handle the renormalization problem in weak interactions. One is the heavy-photon version $B^0$ of Lee and Wick[16] (in this model no neutral spin-0 boson need be introduced because the electromagnetic current is conserved[17]).

The predicted leptonic width[18] is, however, $\Gamma_{B^0} = \frac{2}{3}\alpha m_{B^0} = 15.1$ MeV if $B^0 = X(3.105)$; hence there is significant disagreement with Eq. (4). The recent attempt[19] to construct renormalizable models of weak interactions including neutral currents allows for scalar intermediate bosons $B^0$ and $\overline{B}^0$. Unfortunately in the simplest version discussed by Segrè[19] the $B^0$ and $\overline{B}^0$ are of heavy mass ($m_B \approx 300$ GeV) and appear not to be coupled to lepton pairs $l\bar{l}$ (where $l = \mu, e$).

Finally, the old schizon model[20] and its variants,[21] which allow for spin-1 bosons $X^0$ (and $\overline{X}^0$), would predict electronic width far smaller than that observed for $X^0(3.105)$ (by a factor of $10^3$–$10^4$) if current experimental branching ratios for $K^+ \to \pi^+ + e^+ + e^-$ and $K_L^0 \to \mu\bar{\mu}$ are taken into consideration.

It must also be stressed that the intermediate-neutral-boson approach would be in severe difficulties if the spectrum of $X^0$ states in the $e^+$-$e^-$ system should prove to be much richer than presently uncovered.

### C. Gauge-related models

There are two possibilities:

(i) $X$ may be a neutral intermediate vector boson $Z$;

(ii) $X$ may be a Higgs scalar $\phi$.

Let us consider first the vector-boson case (i). In most of the recent plethora of gauge models (see Bjorken and Llewellyn Smith[22] for a statistically significant sample of such models), the vector bosons are heavy:

$$m_W > 37 \text{ GeV and } m_Z/m_W > 1\,;$$

hence identifying $X$ with $Z^0$ does not represent a feasible possibility.

In the original Georgi-Glashow model,[23] the $W$ boson can be light; however, the model contains no $Z^0$ boson. Another exception in this class is the Bég-Zee model[24] in which the $Z$ boson can have a small mass. However, if $X$ is identified with this $Z$, we find

$$\Gamma_{Z\to e^+ + e^-} \cong \frac{1}{12\pi}\frac{e^2}{\sin^2\xi}\, m_Z\,.$$

The experimental limit on $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ implies $0.01 < \sin^2\xi < 0.07$. This leads to 8 MeV $< \Gamma_{Z\to e^+e^-} < 58$ MeV, which is too large a leptonic width for the identification $X = Z$ to be relevant.

Under category (ii) the Higgs scalar $\phi$ in most of the gauge models has a coupling to leptons proportional to the mass of the lepton and hence $\Gamma_{\phi\to\mu^+\mu^-}/\Gamma_{\phi\to e^+e^-} = (m_\mu/m_e)^2$. This rules out the identification of $X$ with the scalar $\phi$ occurring in most models of this type, since the $X$ decay widths into muon pair and electron pair are expected to be comparable and given by Eq. (4). Again the Georgi-Glashow model[23] is an exception since this model involves a Higgs scalar $\phi$ whose coupling to electrons and muons is essentially proportional to the corresponding heavy-lepton masses, namely $m_{E^+}$ and $m_{M^+}$, respectively. In this model[25]

$$\Gamma_{\phi\to e^+e^-} = \tfrac{1}{8}\,\alpha\,(m_{E^+}/m_W)^2 m_\phi\,.$$

Using $m_\phi = 3.1$ GeV, $m_{E^+} > 6$ GeV,[26] $m_W < 53$ GeV,[23] we get

$$\Gamma_{\phi\to e^+e^-} \geq 36 \text{ keV}\,,$$

which is perhaps too large.

Of course, the Georgi-Glashow model does not have neutral weak currents. Hence the observed muonless neutrino scattering events are to be interpreted as arising from the $t$-channel $\phi$ exchange in the production of a neutral heavy lepton $M^0$ via $\nu_\mu + p \to M^0 +$ hadrons. The $M^0$ has to be light enough to be produced in the CERN-Gargamelle experiment. Parametrizing the $(\nu_\mu M^0 \phi)$ coupling constant by $e\sin\beta\,(m_{E^+}/2m_W)$ in this model and characterizing the hadronic coupling constant by $f$, we get the effective strength for the "neutral-current" interaction:

$$\frac{G_F\lambda}{\sqrt{2}} = e\sin\beta\,(m_{E^+}/2m_W)\,\frac{1}{m_\phi^{\,2}}\, f \quad (\lambda \sim 0.6)\,.$$

Combining this equation with $e^2\sin^2\beta/4m_W^{\,2} = G_F/\sqrt{2}$, and using the available information on the masses $m_\phi$, $m_{E^+}$, and $m_W$, we get an upper bound on $f$ which leads to

$$\Gamma_{\phi\to\text{hadrons}} \simeq f^2 m_\phi \leq 40 \text{ keV}\,,$$

which is perhaps too small. Note that according to this interpretation, the neutral-current interaction is a scalar-type interaction.

We can interpret the purely leptonic neutral-current events in the manner of $\bar{\nu}_\mu + e^- \to \overline{M}^0 + e^-$ again with $t$-channel $\phi$ exchange. The effective coupling constant for this process is

$$e\sin\beta\,(m_{E^+}/2m_W)\,\frac{1}{m_\phi^{\,2}}\,\frac{e m_{E^+}}{2m_W} = \frac{G_F}{\sqrt{2}}\,(m_{E^+}^{\;2}/m_\phi^{\,2}\sin\beta)\,.$$

The factor $(m_{E^+}^{\;2}/m_\phi^{\,2}\sin\beta)$ should be $\lesssim 1$. This is then in contradiction with known data if $m_\phi = 3.1$ GeV since $m_{E^+} > 6$ GeV.[26]

Hence, $X$ does not seem to fit into any of the known gauge models. Going back to the vector-boson interpretation (i), the reason why the gauge models require heavy intermediate bosons is the required relationship with electromagnetism. The price of unification of weak and electromagnetic interactions is the *heavy* intermediate boson. One may take the point of view that this is too heavy a price to pay. So, let us abandon the ambitious aim of unifying weak with electromagnetic interactions and try to build a gauge model of weak interactions alone (charged-current + neutral-current interactions).

Sakurai's model[11,12] connects $X$ to the neutral-current weak interaction. What we propose to do is to try to connect these with the charged current also. Of course our model will also require a substantial variation with $Q^2$ for neutral-current cross sections due to the boson propagator.

We introduce a heavy neutral lepton $\nu_H$ and write $\nu' = \nu \sin\phi + \nu_H \cos\phi$. Assume next that the doublet $\psi = \binom{\nu'}{e}$ has the gauge coupling $g\bar{\psi}\vec{\tau}\gamma_\mu(1+\gamma_5)\psi\cdot\vec{W}_\mu$, where the triplet $\vec{W}$ is composed of the charged components $W^\pm$ and the neutral component $Z^0$. Let their masses be $m_W$ and $m_Z$, which will be assumed to be different. We shall not speculate on the origin of this symmetry breaking. Extension of this model to muons and hadrons on the basis of muon-electron universality and lepton-hadron universality leads to the following relationships:

$$\Gamma_{Z\to e^+e^-} \sim \Gamma_{Z\to\mu^+\mu^-} = g^2 m_Z/6\pi\,,$$
$$\frac{g^2\sin^4\phi}{m_Z^2} = G_F\lambda/\sqrt{2}\,, \tag{6}$$
$$2g^2\sin^2\phi/m_W^2 = G_F/\sqrt{2}\,.$$

The second and third relations refer to the strengths of the neutral-current (which is pure $V-A$ in this model[27]) and charged-current weak interactions, respectively. Setting $\lambda \sim 0.6$ as suggested recently[27] and $m_W \geq 5$ GeV, we get $\sin^2\phi \leq 0.46$ and $g^2 \geq 2\times 10^{-4}$, which leads to

$$\Gamma_{Z\to e^+e^-} \geq 33 \text{ keV}\,,$$

and is perhaps too large. If we choose the optimal values $\lambda \sim 0.75$ (consistent with the CERN-Gargamelle values when interpreted in a $V-A$ type model) and $m_W \approx 4$ GeV (which is barely compatible with data[28] on the lower limit for the $W$ mass), we get $\Gamma_{Z\to e^+e^-} \approx 10$ keV.

A more complicated model is obtained by mixing the electron also with a heavy charged lepton $e_H$. In other words, use $\psi = \binom{\nu'}{e'}$, where $e' = e\sin\chi + e_H\cos\chi$. Then we have

$$\Gamma_{Z\to e^+e^-} = g^2\sin^4\chi\,(m_Z/6\pi)\,,$$
$$\frac{g^2\sin^4\phi}{m_Z^2} = G_F\lambda/\sqrt{2}\,, \tag{7}$$
$$\frac{2g^2\sin^2\phi\sin^2\chi}{m_W^2} = G_F/\sqrt{2}\,.$$

There is the appearance of more freedom in this model because of the presence of two mixing angles $(\phi, \chi)$. However, there is one angle-independent relation which is unique to this entire class of models:

$$\Gamma_{Z\to e^+ + e^-} = \frac{G_F m_W^4}{4\sqrt{2}\,(6\pi)\lambda m_Z}\,. \tag{8}$$

Hence the problem of the large leptonic width we encountered earlier persists.

The next artifice we try is to mix the neutral vector bosons. Let us write the basic gauge coupling of $\psi = \binom{\nu}{e^-}$

$$g\bar{\psi}\vec{\tau}\gamma_\mu(1+\gamma_5)\psi\cdot\vec{W}_\mu + g'\bar{\psi}\gamma_\mu(1+\gamma_5)\psi U_\mu\,. \tag{9}$$

We have taken the isoscalar current to be $V-A$, but other choices such as pure vector are also possible. We assume that the neutral vector boson $W^3$ and $U$ mix (this could be the origin of the symmetry breaking) to produce the physical bosons

$$Z_1 = U\cos\theta + W^3\sin\theta\,,$$
$$Z_2 = -U\sin\theta + W^3\cos\theta\,, \tag{10}$$

which may be identified with the two bosons seen in the $e^+e^-$ experiments.[2,3] We now get

$$\Gamma_{Z_1\to e^+e^-} = (-g\sin\theta + g'\cos\theta)^2 m_{Z_1}/6\pi\,,$$
$$\Gamma_{Z_2\to e^+e^-} = (g\cos\theta - g'\sin\theta)^2 m_{Z_2}/6\pi\,,$$
$$\frac{1}{m_{Z_1}^2}(g\sin\theta + g'\cos\theta)^2 + \frac{1}{m_{Z_2}^2}(g\cos\theta - g'\sin\theta)^2 = G_F\lambda_p/\sqrt{2}\,,$$
$$\frac{1}{m_{Z_1}^2}(-g^2\sin^2\theta + g'^2\cos^2\theta) + \frac{1}{m_{Z_2}^2}(-g^2\cos^2\theta + g'^2\sin^2\theta) = G_F\lambda_n/\sqrt{2}\,,$$
$$2g^2/m_W^2 = G_F/\sqrt{2} \quad (\text{Cabibbo angle } \theta_C \approx 0) \tag{11}$$

where $\lambda_p$ and $\lambda_n$ are the strengths of the neutral-current interactions in $\nu + p \to \nu + p$ and $\nu + n \to \nu + n$, respectively. The problem of the large leptonic width for $Z_1$ can be solved by choosing $(\theta, g')$ suitably small. However, this will lead to a large leptonic width for $Z_2$ which can be confronted with experiment[3] on the $X(3.695)$.

Clearly in this approach we can incorporate a still larger number of neutral vector bosons (whose existence seems to be indicated[3]) by enlarging the gauge group to SU(3), SU(3)×SU(3), or even higher groups.

### D. Abnormal $C$-parity particles; electromagnetic current with color triplet piece

This class of models generally need to assume unusual properties for the electromagnetic current. It has been pointed out by Gell-Mann[29] that particles with abnormal $C$ parity (i.e., with opposite transformation properties under particle-antiparticle conjugation $C$ to those of the normal meson isospin or octet multiplets) generally have low production rates in strong interactions (and hence may be missed) as well as small width because of the absence of $q\bar{q}$ coupling among other considerations. If $X(3.105)$ or $X(3.695)$ is identified with the proposed unitary singlet $h$ particle[30] with $(J^P, I^G) = (1^-, 0^+)$ the strong decays will be dominated by two-body channels such as $\rho\rho$, $\omega\omega$, $K^*\bar{K}^*$, and $K^*\bar{K} + \bar{K}^*K$, which can be large (of order of a few hundred MeV) since $h$ has now a rather large mass but yet low spin and hence low barrier factors (decays to $K^+K^-$ and $\pi^+\pi^-$ exclusive channels unaccompanied by neutrals are forbidden by conservation of $C$ and isospin in strong interactions). This presumes, however, that the strong coupling of $h$ is comparable to that of the usual mesons. The absence of abnormal $C$-parity mesons in strong production processes (at least for masses up to 2 GeV) suggests that their production cross section is down by a factor of order $10^{-2}$–$10^{-3}$ from that for the usual mesons. Assuming the same reduction factor in the width estimate will lead to $\Gamma_h \sim 1$ MeV[31]; hence as with the charmonium model ($q_C\bar{q}_C$) discussed in (a) *optimism* (or a good dynamical theory) is needed to realize agreement with the hadronic width delineated in Eq. (4).

The production of $h$ or $X$ via single photon exchange in $e^+e^-$ requires, however, the introduction of a $C$-violating unitary singlet $K_\mu$ hadronic electromagnetic current[30] which, in the field-current identity framework, will lead to relations of the type $K_\mu(x) = -(m_h^2/g_h)h_\mu(x)$, where $m_h$ is the mass[32] of $h$ or $X$, and $g_h = \langle 0|K_\mu|h\rangle$. This in turn requires the rather peculiar dynamical assumption that $C$ violation is prominent for massive timelike photons but yet attenuated for low-energy phenomena. It would nevertheless be interesting to test $C$ violation in $e^+$-$e^-$ colliding beams at the SPEAR-type energy. Such tests have been proposed by Pais and Treiman.[33]

As a really exotic suggestion, *purely* to understand the hadronic width piece of the $X$ anomaly, we may propose that $X(3.105)$ is a color octet boson ($J^{PC} = 1^{--}$) and that the electromagnetic current has a color triplet piece (e.g., $\bar{\mathcal{P}}_i\gamma_\mu\mathcal{P}_j$ in quark language where $i, j$ are color indices). The $X$ strong decay to hadrons is forbidden because the usual hadrons are color singlets; $X$ decay to hadrons $+\gamma$ is forbidden because $\gamma$ has only color singlet plus color triplet pieces. Allowed decays are then $X \to$ hadrons $+ 2\gamma$ and

$$X \xrightarrow[2-\text{virtual }\gamma]{} \text{hadrons}$$

since $3\times 3^*$ for the two photons does have an octet piece for coupling to $X$. The hadronic width is then of order $\alpha^2 m_X$, which is compatible with the data. The difficulty with this model is that we cannot explain how $X$ is produced in $e^+e^-$ with the known cross section, nor is it possible to understand the leptonic width of $X$.

In conclusion we wish to emphasize that none of the schemes proposed above represents a completely satisfactory interpretation of the $e^+e^-$ anomalies, given the over-all constraining experimental facts.

*Note added in proof.* To construct the color triplet electromagnetic current mentioned in the text, we need a fourth color and the current is, e.g., $\bar{\mathcal{P}}_4\gamma_\mu\mathcal{P}_i$, where $i$ (=1 to 3) and 4 are color indices.

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[1] J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).
[2] J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).
[3] G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).
[4] Note that independent of mass, a width $\Gamma \sim 100$ KeV corresponds to a lifetime of order $10^{-19}$ to $10^{-20}$ sec.
[5] T. Goldman and P. Vinciarelli, Phys. Rev. Lett. 33, 246 (1974).
[6] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970); S. Weinberg, Phys. Rev. Lett. 27, 1688 (1971).
[7] M. Han and Y. Nambu, Phys. Rev. 139, B1006 (1965); Y. Nambu, in *Preludes in Theoretical Physics*, edited by A. de-Shalit *et al.* (North-Holland, Amsterdam, 1966), p. 133; J. C. Pati and C.-H. Woo, Phys. Rev. D 3, 1173 (1971); G. A. Snow, Nucl. Phys. B55, 445 (1973).
[8] We thank R. Dashen for emphasizing this point.
[9] The order-of-magnitude estimate $\Gamma \sim \alpha M$ may not be unreasonable, since application to $\omega^0 \to \pi^0 + \gamma$ gives 5.7 MeV for the width instead of the observed width of about 1 MeV. However, in $X \to \gamma + h$, the $h$ is now an inclusive sum over *all* possible hadrons, not just the exclusive $\pi^0$ as in $\omega^0 \to \pi^0 + \gamma$.
[10] R. Dolen, D. Horn, and C. Schmid, Phys. Rev. Lett. 19, 402 (1967); Phys. Rev. 166, 1772 (1968); M. Greco, Nucl. Phys. B63, 398 (1973); J. J. Sakurai, in Proceedings of the Erice Summer School (to be published).
[11] J. J. Sakurai, Phys. Rev. Lett. 34, 56 (1975).
[12] J. J. Sakurai, Phys. Rev. D 9, 250 (1974).
[13] S. L. Adler (private communication).

[14]See S. L. Adler, S. Nussinov, and E. A. Paschos, Phys. Rev. D 9, 2125 (1974). (In particular, compare columns three and seven of Table II for $\sin^2\theta_W = 0.5$.)

[15]W. Lee *et al.*, report to the XVII International Conference on High Energy Physics, London, England, 1974 (unpublished). Also P. Sokolsky (private communication).

[16]T. D. Lee and G. C. Wick, Phys. Rev. D 2, 1033 (1970).

[17]T. D. Lee, Phys. Rev. Lett. 26, 801 (1971).

[18]T. D. Lee, in *Proceedings of the Topical Conference on Weak Interactions, CERN, 1969* (CERN, Geneva, 1969), p. 427.

[19]G. Segrè, Phys. Rev. Lett. 33, 1244 (1974).

[20]T. D. Lee and C. N. Yang, Phys. Rev. 119, 1410 (1960).

[21]S. Pakvasa and S. F. Tuan, Phys. Rev. D 6, 3342 (1972). See also L. Wolfenstein, in *Particles and Fields—1971*, proceedings of the 1971 Rochester meeting of the Division of Particles and Fields of the American Physical Society, edited by A. C. Melissinos and P. F. Slattery (A.I.P., New York, 1971), p. 204.

[22]J. D. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D 7, 887 (1973). See especially Table I in their paper. Note that although model 4 here can be consistent with light vector bosons, there is, however, no neutral "current" coupling to the neutrinos, contrary to data.

[23]H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972).

[24]M. A. B. Bég and A. Zee, Phys. Rev. Lett. 30, 675 (1973); see also A. D. Dolgov, L. B. Okun', and V. I. Zakharov, Phys. Lett. 47B, 258 (1973).

[25]J. Primack and H. R. Quinn, Phys. Rev. D 6, 3171 (1972).

[26]A. De Rújula *et al.*, Rev. Mod. Phys. 46, 391 (1974); see also B. Barish *et al.*, Phys. Rev. Lett. 32, 1387 (1974), where the limit on $m_{E^+}$ has been raised from 6 GeV to greater than 8.4 GeV.

[27]The suggestion that the neutral current be pure $V-A$ has previously been made by S. L. Adler and S. F. Tuan, Phys. Rev. D 11, 129 (1975).

[28]D. H. Perkins, in *Proceedings of the Fifth Hawaii Topical Conference in Particle Physics, 1973*, edited by P. N. Dobson, Jr., V. Z. Peterson, and S. F. Tuan (Univ. of Hawaii Press, Honolulu, Hawaii, 1974), p. 507.

[29]M. Gell-Mann, in M. Gell-Mann and Y. Ne'eman, *The Eightfold Way* (Benjamin, New York, 1964), p. 98.

[30]S. Pakvasa and S. F. Tuan, Phys. Rev. Lett. 20, 632 (1968); see also T. D. Lee, in *Proceedings of the Second Hawaii Topical Conference in Particle Physics*, edited by S. Pakvasa and S. F. Tuan (Univ. of Hawaii Press, Honolulu, Hawaii, 1967), p. 13.

[31]The branching ratio $\Gamma_{h\to l\bar{l}}/\Gamma_{h\to \text{hadrons}}$ would be typically $a^2/(10^{-2}-10^{-3})$, which is in the acceptable range [cf. Eq. (4)].

[32]Fourier decomposition of the propagator $\langle 0|T[K_\mu(x)K_\nu(0)]|0\rangle$ may have more than one complex pole corresponding to possible resonances $h$, $h'$ [$=X(3.695)$?] ..., of *different* masses but with the same set of quantum numbers $(J^P, I^G) = (1^-, 0^+)$, unitary singlet. Because of the lack of coupling to $(q\bar{q})$ the abnormal particle spectrum may not follow the $L$-excitation quark-model classification. Alternative symmetry schemes which relate abnormal mesons with their normal partners have been proposed [cf. S. F. Tuan and T. T. Wu, Phys. Rev. Lett. 18, 349 (1967)].

[33]A. Pais and S. B. Treiman, Phys. Lett. 29B, 308 (1969).