Exotic Mesons and e^+e^- Annihilation

Myron Bander, Gordon L. Shaw, and Paul Thomas
*Department of Physics, University of California, Irvine, California 92717**

and

Sydney Meshkov
National Bureau of Standards, Washington, D. C. 20234
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Recent experiments at SPEAR indicate an unexpectedly large number of 1^{--} states in the energy range 3.9–4.4 GeV. We show how the existence of exotic $c\bar{q}\bar{c}q$ mesons can account for these states as well as the rise in R and the missing $\psi(3.7)$ decays. The width of these states does not require that they lie above the, as yet unobserved, $D\bar{D}$ threshold. Predictions of the model are readily testable.

Recent experiments at SPEAR[1] indicate the production of a plethora of $J^{PC}=1^{--}$ states by e^+e^- annihilation in the energy range 3.9–4.4 GeV. Although the ψ family of narrow resonances below 3.8 GeV can be described adequately as $\bar{c}c$ states of a new "charmed" quark,[2] the existence of *many* closely spaced 1^{--} states around 4 GeV does not fit naturally into a scheme of radial excitations. In this paper we correlate the *assumed* existence of the many 1^{--} states (having somewhat smaller than normal hadronic widths of approximately 20 MeV) with (a) the rise in $R=\sigma(e^+e^-\rightarrow \text{hadrons})/\sigma(e^+e^-\rightarrow\mu^+\mu^-)$ starting at about 3.5 GeV, (b) the missing $\psi(3.7)$ decays, and (c) the large fraction of $\psi(3.7)$ decays into $\psi(3.1)\pi\pi$ and $\psi(3.1)\eta$. The somewhat less than normal widths of the 1^{--} states suggest that they lie below the charmed $D\bar{D}$ threshold, in agreement with the apparent lack of charm production at SPEAR.[3]

The basic dynamical assumption of our model is that the new 1^{--} states are four-quark composites: $(c\bar{q})(\bar{c}q)$, where q denotes the old u, d, and s quarks.[4] The principal predictions include the following: (i) Some of the new states are $I=1$, in addition to the expected $I=0$ ones [the $I=1$ (0) states may decay strongly to even (odd) numbers of pions]. (ii) There exist lower $I=1$, $J=0$ states to which the 1^{--} ones can decay by a single charged pion.

We label the mesonic states as follows:

old mesons,	M,	$q\bar{q}$;
"old exotic" mesons,	M^{ex},	$q\bar{q}\bar{q}q$;
ψ's and χ's,	ψ,	$c\bar{c}$;
charmed mesons,	D,	$c\bar{q}$;
new exotic mesons,	E,	$c\bar{q}\bar{c}q$.

The M's fit well into the $SU(6)\otimes O(3)$ quark model. The possibility of there being M^{ex}'s has long been discussed and they have been searched for with inconclusive results. Recently Jaffe and Johnson,[5] in the context of the Massachusetts Institute of Technology bag model, have suggested that the M^{ex} mesons may be present, but are much broader than the usual M states. The ψ family below 4 GeV is well described as S- and P-wave $c\bar{c}$ states and their narrow widths by the Okubo-Zweig-Iizuka (OZI) rule.[6] The large jump in R, starting around 3.5 GeV, is usually ascribed to the pair production of $D\bar{D}$'s. However the experimental search for D's (below 5 GeV) has led to negative results.[3] We shall assume that the masses of the D's are higher than previously estimated and that they are not produced at SPEAR below 5 GeV. We associate the many 1^{--} states at 4 GeV with E's and the rise in R with nonresonant $E+M$ production.

We restrict our (low-lying) E states to be composites of color singlets (i.e., virtual D's), $c\bar{q}$ (with spin $S_1=0,1$) and $\bar{c}q$ ($S_2=0,1$). The total $\vec{S}$ equals $\vec{S}_1+\vec{S}_2$ and $\vec{J}$ equals $\vec{L}+\vec{S}$, where $\vec{L}$ is the relative angular momentum of the two virtual D's. If we limit q to be u and d quarks, there are eight ($L=1$) $J^{PC}=1^{--}$ E states which couple to the photon, four with $I=0$ and four with $I=1$. There are 32 other $L=1$ and $L=0$ states which we expect to lie nearby in energy, the $L=0$ ones presumably being lower.[7]

Around 4 GeV the following strong decay modes are allowed by the OZI rule:

$$E\rightarrow E'+M,\quad E\rightarrow\psi+M.$$

The reason why these decays are suppressed and the widths of the E's are smaller than the canonical M widths of about 100 MeV is as follows. We have assumed that the quark configuration inside the E's consists of a $\bar{c}q$ and a $\bar{q}c$ pair. In both of the above decay modes at least one of the pairs must break up and a quark rearrangement take place. Such a rearrangement will suppress the rates. The amount of suppression will depend on the details of the wave functions of the virtual D's. No such rearrangement is necessary in the case of M^{ex}'s which can just fall apart into two M's. Estimates[5] of this process yield widths of the order of 500 MeV. The masses of the E's are about 1 GeV above the lowest ψ. In analogy we expect the M^{ex}'s to be about 1 GeV above the M's, where their large widths would make them difficult to observe.[8]

Suppressed by the OZI rule is

$$E \to M + M,$$

as well as

$$\psi \to M + M \text{ and } \psi \to \psi' + M.$$

There are E's which lie close to the $\psi(3.7)$. Thus we expect a small E admixture in the $\psi(3.7)$ [the large mass difference would make any such admixture to the $\psi(3.1)$ negligible]. Such a small admixture in the $\psi(3.7)$ would explain the relatively large $\psi(3.7) \to \psi(3.1)\pi\pi$ and $\psi(3.1)\eta$ decays; if in addition one or more of the E's lies below the $\psi(3.7)$, the decay $\psi(3.7) \to E + \pi$ is possible and might account for the "missing" $\psi(3.7)$ decays.

We suggest the following tests of our model: (1) There are eight 1^{--} E states in the 3.9–4.4-GeV region.[7] (2) There are both $I = 0$ $(G = -1)$ and $I = 1$ $(G = +1)$ states. The $I = 0$ states should preferentially decay into an odd number of pions and the $I = 1$ to an even number. The change in the odd/even ratio should be striking as one moves in energy across the separated resonances. (3) Since there are so many E's and ψ's to which an individual 1^{--} E state can decay, we expect no one decay mode to dominate. In particular we do not expect the inclusive $\psi(3.1)$ (which has an easily identifiable $\bar{l}l$ signature) to be a dominant decay. However, small peaks in the inclusive charged-π distributions might be observed in $E(J^{PC} = 1^{--}, I = 0, 1) \to E^{\mp}(I = 1) + \pi^{\pm}$. These peaks would appear in the inclusive π distribution at small values of the Feynman variable $x_F = 2p_\pi/\sqrt{s}$, where they would be superimposed on a naturally rising background. (An E at 4.4 GeV decaying to one at 3.6 GeV would yield a pion with $x_F \sim 0.3$.)

In addition to the 1^{--} E peaks, we can account for the smooth rise in R, starting at around 3.5 GeV, as being due to the nonresonant (via virtual $D\bar{D}$ pairs) production of $E + M$. As a result of form factors this contribution of virtual $D\bar{D}$ pairs to R will drop off above the real $D\bar{D}$ threshold. Any E's above this threshold are expected to be as broad as the M^{ex}'s. At higher values of s, we expect R to settle down to $3\frac{1}{3}$ plus the contributions of possible heavy leptons and/or new quarks.

In conclusion, we have seen how the existence of exotic $c\bar{q}\bar{c}q$ E mesons can account for (a) many 1^{--} states around 4 GeV, (b) the rise in R starting around 3.5 GeV, (c) the missing $\psi(3.7)$ decays, and (d) the large fraction of $\psi(3.7)$ decays to $\psi(3.1)\pi\pi$ and $\psi(3.1)\eta$. We do not require the existence of low-lying D's to account for the widths of these 1^{--} states. We feel that our model has the additional virtues of being simple and easily testable by experiment. Models involving more than one new quark of similar masses, while allowing for many 1^{--} states around 4 GeV, would predict new very narrow states which are not observed in this energy range. Excitable color models would contain many 1^{--} states, but have difficulty[9] in explaining the nonobservation of color excitation in deep inelastic electron and neutrino production.

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[1]G. Feldman, in *Proceedings of the Conference on Quarks and the New Particles, Irvine, California, 5–6 December 1975* (unpublished); R. Schwitters, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975,* edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975), p. 12.

[2]S. Glashow, J. Iliopoulous, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[3]Charmed particles have not as yet been seen at SPEAR (see Ref. 1). However, they may have been seen in ν scattering: A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1203 (1975). There is, however, no information on their possible masses and from the lack of evidence in other searches, we *assume* that they lie higher than would be necessary for the new 1^{--} states to decay into pairs of them.

[4]The initial motivation that led us to exotics was that we needed a mechanism that could give many states of the same spin and parity. Examples of the excitation of many states of the same spin and parity, but differing only in some unobserved quantum number, abound in nuclear physics. For example, the excitation of the giant dipole resonance in light nuclei is described as the collective excitation of many particle-hole states of $J^P = 1^-$, differing only in the shell-model orbitals of the various states.

[5]R. L. Jaffe and K. Johnson, Massachusetts Institute of Technology Report No. 508 (unpublished).

[6]S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, CERN Report No. 8419/TH412, 1964 (unpublished);

I. Iizuka, Prog. Theor. Phys., Suppl No. 37-38, 21 (1966).

[7]In addition, s quarks can contribute, which would introduce four more 1^{--} and sixteen other $L=0$ and 1 states. However their decays would involve $K\bar{K}$. Thus we would expect phase space to make them *very* narrow.

[8]This reason for not observing M^{ex}'s is different from the one proposed by P. G. O. Freund, R. Waltz, and J. Rosner, Nucl. Phys. B13, 237 (1969). They propose a rule for exotic couplings in which each of the three hadrons at a vertex exhanges at least one quark line with each of the remaining two. This rule prevents copious M^{ex} production.

[9]For a review of the difficulties in the color model see H. Harari, in *Proceedings of International Conference on Lepton and Photon Interactions at High Energies, Stanford, California, 1975*, edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975), p. 317; C. H. Llewellyn-Smith, *ibid.*, p. 709. Suppression of the excitations in the color model has been considered by J. Pati and A. Salam, Phys. Rev. Lett. 36, 11 (1976).

Have Mesons Composed of Charmed Diquarks Been Discovered?

Carl Rosenzweig*
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260
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I suggest that the structure observed between $\sqrt{s}=3.9$ and 4.5 GeV at SPEAR is due to the presence of exotic mesons composed of a charmed diquark and antidiquark. Arguments for the existence of such mesons are reviewed. The characteristic features, i.e., masses, narrow widths, and abundance, which enable them to explain the data are presented. Further properties and yet another narrow meson with $m \approx 6.7$ GeV/c^2 is predicted.

For many years theoretical physicists have been predicting[1,2] the existence of a new class of mesons, different from those obtained from a quark and an antiquark ($q\bar{q}$). There is evidence[3] that the nucleon-antinucleon system possesses bound states and resonances which may belong to exotic representations. There is also support from triple-Regge analysis[4] for an exotic exchange with intercept $-0.6 \geq \alpha(0) \geq -1.6$. Nevertheless the actual existence of such exotic resonances has yet to be convincingly demonstrated and one can say that exotic mesons are a theoretical concept in search of experimental confirmation.

Baryon spectroscopy is considerably more simple than implied by the three-body (qqq) naive quark model. There is strong evidence[5] that the only SU(6) baryon supermultiplets are $\underline{56}$'s with even L and $\underline{70}$'s with odd L. Such a striking pattern is most easily understood by assuming that baryons are composed of a quark and a diquark which interact via an exchange force.[6] Diquarks come in two varieties, symmetric in SU(6) [SU(8)]: spin-1 members transforming as $\underline{6}$ ($\underline{10}$) for SU(3) [SU(4)] and spin-0 members transforming as $\underline{3}^*$ ($\underline{6}$). I call these diquarks Δ and δ, respectively, and adopt the viewpoint that the regularities of the baryon spectrum imply that diquarks serve as building blocks for constructing hadrons. Diquarks have also proven useful in other areas of strong interactions.[7,8] While the nature of diquarks has received some theoretical study,[7,9,10] there is as yet no firm understanding of their structure. They are an experimental regularity in search of theoretical approval.

Exotic mesons composed of diquarks.—Once we accept diquarks, we are naturally led (even forced) to consider objects composed of a diquark and an antidiquark (hereafter referred to as diquark or d mesons). d mesons are the most economical way to introduce exotics. Remarkably, the minimal solution[11] to the baryon-antibaryon duality constraints, without any reference to baryon structure, requires precisely the exotic spectrum generated by the δ and Δ diquarks. One finds[10,11] a d-meson spectrum exhibiting a generalized "ideal" mixing in which d mesons precipitate into groupings according to diquark masses. The solution is closed and duality does not require additional states. Theoretical prejudices and baryon phenomenology can have a happy marriage with exotic d mesons the offspring.

It is clear that d mesons will couple strongly to $B\bar{B}$. If diquarks are really point particles, decay into nonexotic mesons is strictly Okubo-Zweig-Iizuka[12] (OZI) forbidden. The diquark construction of exotics thus provides[10] a rationale for previously given[1] selection rules for exotic