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Exotic Mesons and e^+e^- Annihilation

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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 $R=\sigma(e^+e^-\to \text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ 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:

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

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).

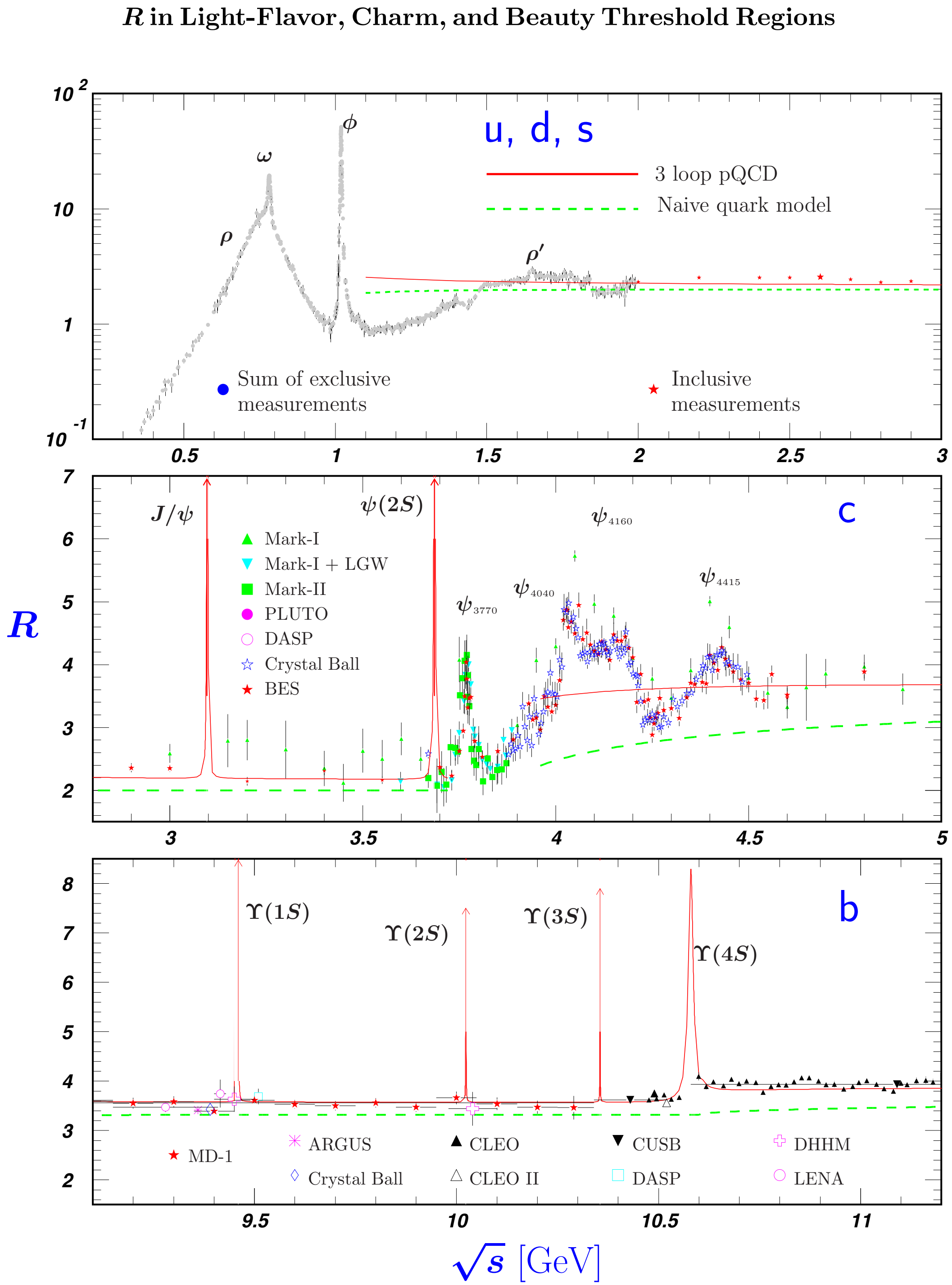
[6]S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, CERN Report No. 8419/TH412, 1964 (unpublished);

"You will soon have a brilliant idea. Unfortunately, it won’t be any better than the rest of the ones that you have had recently."

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

where the denominator is the lowest-order QED cross section,

$$= \frac{4\pi\alpha^2}{3s}$$



$c\bar{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
• $X(3915)$	$0^+(?^{?+})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^{\pm}$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^{\pm}$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^{\pm}$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

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charmed mesons,	D,	$c\bar{q}$;
new exotic mesons,	E,	$c\overline{qc}q$.

Using the decay $\psi(4160) \to X(3872)\gamma$ to probe the molecular content of the $X(3872)$

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Abstract

The $X(3872)$ has non-charmonium-like properties, such as decay processes that seem to violate isospin, and a mass that lies unexpectedly close to the $D^0\ \bar{D}^{0*}$ threshold. An EFT that includes both charmonium-like (short distance) and molecule-like (meson bound state) properties is used to analyze the $X(3872)$ as it is produced in the decay of $\psi(4160)$. This is a route that BESIII may be able to measure. We find that the correlation between the angular distribution of the outcoming photon (or $X(3872)$) and the polarization of the $\psi(4160)$ source may be used to provide information on whether short-distance or long-distance effects dominate.

arXiv:1304.8101

The $X(3872)$ was discovered by the Belle collaboration [1] as a narrow resonance from the decay $B^{\pm} \to X(3872)K^{\pm}$, $X(3872) \to J/\psi\pi^{+}\pi^{-}$. Its existence has been confirmed by the CDF [2], D0 [3], and BaBar [4] collaborations, and now at the LHC [5, 6]. The most recent Particle Data Group value for its mass is $m_{(X)} = 3871.68 \pm 0.17$ [7], but whether it is actually above or below the $D^0\ \bar{D}^{0*}$ threshold at 3871.81 ± 0.36 MeV is still an open question. The Belle collaboration finds an upper limit on the width of the $X(3872)$ to be $\Gamma_{(X)} < 1.2$ MeV at a 90 percent confident level [8].

While uncertain for most of the time since its discovery, the J^{PC} quantum number assignments for the X(3872) are now known to be 1^{++} [9]. This, along with the closeness of the $X(3872)$ to the $D^0\ \bar{D}^{0*}$ threshold, makes it possible for the X(3872) to be interpreted as a loosely bound state of D^0 and $\bar{D}^{0*}$ mesons. The possibility that mesons could themselves form "molecular" bound states of other mesons was discussed in Ref. [10] and for charmed mesons in particular in Refs.[11–15]. The $X(3872)$ was investigated as a potential molecule shortly after its discovery in Refs.[16–20]. It seems certain that there is at least a component of the $X(3872)$ that can be taken as a molecule given that it will likely strongly mix with the C=+1 combination of the neutral D mesons. Exactly how much of it is molecular, what else might describe its wavefunction, and what observables should be studied to unravel it are the subject of lively debate in the literature.

Determination of the $X(3872)$ meson quantum numbers

The LHCb collaboration†

Abstract

The quantum numbers of the $X(3872)$ meson are determined to be $J^{PC} = 1^{++}$ based on angular correlations in $B^+ \to X(3872)K^+$ decays, where $X(3872) \to \pi^+\pi^- J/\psi$ and $J/\psi \to \mu^+\mu^-$. The data correspond to 1.0 fb^{-1} of pp collisions collected by the LHCb detector. The only alternative assignment allowed by previous measurements, $J^{PC} = 2^{-+}$, is rejected with a confidence level equivalent to more than eight Gaussian standard deviations using the likelihood-ratio test in the full angular phase space. This result favors exotic explanations of the $X(3872)$ state.

arXiv:1302.6269


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