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?

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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 $m\approx 6.7\ \mathrm{GeV}/c^2$ 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 $-0.6\geqslant\alpha(0)\geqslant-1.6$. 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 mesons.

If the mass of the d meson is below the relevant $B\bar{B}$ threshold, the hadronic decay widths are small. Since diquarks have structure, one does, however, expect decays into mesons to occur. For example, q-$\bar{q}$ interchange can take place whereupon the d meson will fall apart into two $q\bar{q}$ states. The corresponding width will be greater than that for a strictly OZI-forbidden decay $[\Gamma(\varphi \to \rho\pi)]$ but smaller than typical meson widths $[\Gamma(\rho)]$. A more quantitative estimate is obtained by taking seriously the estimated widths of narrow $N\bar{N}$ states.[2] In this context narrow means 10–20 MeV.

It is an empirical fact[13] that resonances appear close to thresholds. Since mesons with hidden charm display a tendency to fall below relevant thresholds (e.g., $m_\psi < 2m_D$ but $m_\varphi > 2m_K$), I would not be surprised if some d mesons with hidden charm are below threshold for charmed-baryon production.

Spectroscopy of 1^{--} d mesons with hidden charm.—Charmed quarks form diquarks in conjunction with u, d, s, and c. From these I construct four families of d mesons with hidden charm. The 1^{--} members I label ρ_d, ω_d, φ_d, and ψ_d. Since ω_d has $I=0$ it will mix with φ_d and the ψ mesons. I therefore expect the ρ_d-ω_d degeneracy to be broken at least as much as for ρ-ω (10–20 MeV). φ_d contains two strange quarks and thus $m_{\varphi_d} - m_{\rho_d} \approx 2(m_s - m_{u,d}) \approx 200$–$300$ MeV.

The ρ, ω, and φ diquark mesons come in three varieties: $\delta\bar{\delta}$, $\delta\bar{\Delta}$ (degenerate with a 1^{-+} family), and the two states which can be formed from $\Delta\bar{\Delta}$. ψ_d comes only in the $\Delta\bar{\Delta}$ doublet. In a diquark model, the masses of the normal baryons lead[7,14] to the estimate $m_\Delta - m_\delta \approx 200$–$300$ MeV. If this is true for charmed diquarks the $\delta\bar{\Delta}$ and $\Delta\bar{\Delta}$ states will be considerably more massive than $\delta\bar{\delta}$. On the other hand theoretical arguments suggest[15] $m_\Delta - m_\delta \propto m_c^{-1}$, which implies a much smaller mass difference. The large hyperfine mass splitting observed between ψ and η_c makes one wary of these simple arguments. Nevertheless, we cannot confidently estimate the mass splittings between d-meson varieties beyond the broad limits of 100–600 MeV.

Everyone[15] has his own secret formula for computing masses of hadrons containing charmed quarks. All such estimates for the mass of the lowest-lying ρ_d should be in the range 3.8–4.5 GeV. (In a 1^{--} meson the diquarks are in a relative P state. This orbital excitation typically costs ~0.5 GeV of mass.) This is precisely the energy where such structure is observed at SPEAR,[16] and is below common estimates of charmed-baryon threshold. Narrow d mesons become prime candidates to explain this structure.

Hadronic and leptonic decays of d mesons.—The most likely decays of d mesons, below $B\bar{B}$ threshold, involve quark rearrangement. $\rho_d, \omega_d \to D\bar{D}$ and $\varphi_d \to F^+F^-$ involve the exchange of a noncharmed diquark and are expected to predominate. Decays leading to a $c\bar{c}$ state will also occur but since they require a charmed-diquark exchange I expect them to be suppressed $\sim (m_{qq}/m_{qc})^2$ relative to the prevalent modes. As much as 5–10% of the decays of hidden-charm d mesons may involve $c\bar{c}$ states, divided about equally between η_c (e.g., $\omega\eta_c$) and ψ (e.g., $\eta'\psi$). $\varphi\eta_c$ should only be seen in φ_d decays and if observed would be a particularly clean signal for η_c. For comparison, $\psi''(4.4) \to \varphi\eta_c$ can be computed within a framework successfully applied to ψ and ψ' decays.[17] This yields a value ≤ 50 keV. A substantial decay rate into $\varphi\eta_c$ (~1 MeV) could then qualify a structure as a φ_d rather than as a multiprimed ψ. Decays into all normal hadrons are strictly OZI forbidden and hence negligible.

Since the diquarks are in a relative P state there is a centrifugal barrier [e.g., $(a/R)^{2l}$ with a an annihilation radius $\sim 1/m_\delta$ and R a typical size for a d meson] suppressing decays into e^+e^- by at least an order of magnitude. In fact it is uncertain whether one will be able to couple 1^{--} d mesons sufficiently strongly to e^+e^- for them to be relevant to the SPEAR structure. The analysis will be further complicated by the expected mixing between ω_d, φ_d, and ψ states, and the fact that diquarks are not point particles. I expect that 1^- d mesons will couple to e^+e^-, but relatively weakly. Disregarding all possible complications I record the (charge)^2 ratio for ρ_d:ω_d:φ_d:ψ_d, 9:25:2:32, and suggest that the partial widths to e^+e^- obey this ratio.

Mesons with four charmed quarks.—One of the more interesting predictions of the d-meson picture is the existence of mesons containing four charmed quarks. An estimate of the mass of the two 1^{--} states would be $2m_\psi + 0.5 \approx 6.7 \pm 0.5$ GeV ($\frac{1}{2}$ GeV errors should be sufficiently generous). We might, again, expect at least one and possibly both states to be below the threshold for doubly charmed baryons, and should therefore see yet another narrow resonance(s) at SPEAR. Because all constituent quarks are heavy, $\Gamma(\psi_d) < \Gamma(\varphi_d)$. A preponderent fraction of final states of ψ_d decay should contain only $c\bar{c}$ mesons (e.g., $\psi\eta_c$, $\psi\epsilon_c$). Since ψ is easily detected, the most appropriate place to study charmonium spectroscopy at SPEAR may be at $\sqrt{s}=6.7$ GeV!

d mesons and structure at SPEAR.—The simplest scenario invoking d mesons to explain the observed structure in e^+e^- experiments is as follows. The state at 4.4 GeV is φ_d. It is known[16] to have $\Gamma_{e^+e^-}$ at least an order of magnitude smaller than $\Gamma(\psi\to e^+e^-)$. Approximately 300 MeV below this is the $\rho_d\omega_d$ doublet. Another structure (e.g., that at 3.95 GeV,[16] probably just above $D\bar{D}$ threshold) would be a ψ''. The other d mesons all lie above 4.4 GeV and have not yet been observed and/or are above appropriate $B\bar{B}$ thresholds and are broad. Because of the uncertainty involved in $m_\Delta - m_\delta$ and in d-meson couplings to e^+e^-, many other possibilities can be envisaged. At one extreme $m_\Delta - m_\delta$ might be so small that all $\delta\bar{\delta}$, $\delta\bar{\Delta}$, and $\Delta\bar{\Delta}$ states lie between 3.9 and 4.4 GeV. Some d-meson e^+e^- couplings could be so suppressed that they would not be noticeable above background. The interested reader is urged to construct his own scenario. Unfortunately we have lost predictive power, but the properties of d mesons may be sufficiently distinctive to establish their reality, and distinguish them from other possibilities.[18]

If d mesons exist they will be exceedingly numerous, populating the $\underline{1}$, $\underline{15}$, $\underline{20}$, $\underline{45}$, and $\underline{84}$ representations of SU(4). Eventually these partners of the ρ_d, ω_d, φ_d, and ψ_d should be seen. About 500 MeV below the ρ_d are mesons with diquarks in relative S states. Some of these may lie between ψ and ψ'. What properties d mesons will exhibit when there is no centrifugal barrier separating the diquarks is unclear. One pair of $q\bar{q}$ may readily annihilate causing strong mixing with $q\bar{q}$ mesons or making the diquark concept less meaningful. An extreme example of this latter possibility has been proposed within the framework of the bag model.[19] The observed 0^+ mesons ($\epsilon, \delta, \ldots$) are interpreted as loosely bound $qq\bar{q}\bar{q}$ states. While such an interpretation is at variance with my ideas about diquarks, uncertainties arising from centrifugal effects render comparison premature.

The question all readers are probably asking is "Why have we not seen d mesons made from old quarks?" My answer is that (a) maybe we already have[3,4]; (b) under the best of circumstances such mesons are difficult to detect. Since the 1^{--} d mesons considered here couple strongly to baryon-antibaryon channels, one expects to find them in backward-production experiments which involve antibaryon exchange. Such experiments have been conducted[20] but are not yet sufficiently accurate to rule out the production of the exotic d mesons at the rate expected from duality arguments. Furthermore, if the d-meson masses are greater than the relevant baryon-antibaryon thresholds (a situation different from that envisaged for d mesons composed of charmed diquarks but possibly presaged by the φ-ψ comparison above), the task of finding and distinguishing several broad mesons with widths comparable to their spacings would seem formidable.

The proposed explanation for the observed structure in e^+e^- is conceptually economic. It draws heavily on old ideas and reinforces old prejudices (e.g., duality). Attention is focused on diquarks and the dynamics of their constitution. If the answer to the title question is positive, I expect this problem to be addressed with renewed vigor.[21]

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Note added.—After this work was submitted I became aware of two articles expressing somewhat similar ideas.[22,23] The discovery of a vector meson with mass ≈6 GeV has also been announced.[24] This meson may be the predicted ψ_d meson. In fact if the separation of the ψ_d doublet is only ≈100 MeV, both these mesons may be within the observed structure. A confirmation of this identification would be the observation of copious decay into $\psi\eta_c$ as discussed in the text.

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[2] L. N. Bogdanova, O. D. Dal'karov, and I. S. Shapiro, Ann. Phys. (N.Y.) 84, 261 (1973). Herein is provided the arguments based on the classical nuclear physics of a one-boson-exchange potential for the existence of $N\bar{N}$ bound states and resonances. True to the spirit of "nuclear democracy" I take these states to be the *same* ones whose existence is predicted in Ref. 1 by very different arguments. Imposing the consistency between the two approaches implied by this identification should lead to interesting constraints.

[3] *Proceedings of the Fourth International Symposium on $N\bar{N}$ Interactions, Syracuse, New York, 1975,* edited by T. E. Kalogeropoulos and K. C. Wali (Syracuse Univ.,

Syracuse, N. Y., 1975). The most recent comprehensive review of all aspects of the $N\bar{N}$ system is to be found here. (Further discussion on the subject of $N\bar{N}$ bound states can be found in I. S. Shapiro *et al.*, *ibid.*; C. B. Dover, H. P. Durr, D. M. Tow, and D. Weingarten, *ibid.*)

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[6] D. B. Lichtenberg, Phys. Rev. 178, 2197 (1968).

[7] J. D. Bjorken, unpublished. I wish to thank Professor Bjorken for generously sharing with me some of his ideas and insights about diquarks.

[8] G. Chu has pointed out (unpublished) that by counting diquarks as one unit in a parton model one can reproduce the mnemonic for the band structure observed by J. J. Aubert *et al.*, Phys. Rev. Lett. 35, 639 (1975).

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[13] J. L. Rosner, Phys. Rev. D 6, 2717 (1972).

[14] In a baryon diquark model an $\underline{8}$ is a mixture of δq and Δq; $\underline{10}$ is Δq; $\underline{1}$ is δq. One can then arrive at the estimates quoted.

[15] See, e.g., A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. D 12, 147 (1975).

[16] R. Schwitters and F. J. Gilman, 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).

[17] C. Rosenzweig, University of Pittsburgh Report No. 56 (to be published).

[18] M. Arik, D. D. Coon, and S. Yu, "Psion Mass Spectrum" (to be published).

[19] R. Jaffe and K. Johnson, Phys. Lett. 60B, 201 (1976); I wish to thank R. Jaffe for discussions about exotic mesons and bags.

[20] For a recent review, see R. Panvini, in Proceedings of the Meeting on New Directions in Hadron Spectroscopy, Argonne, Illinois, 7–10 July 1975, CONF 750729 (unpublished).

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Observation of a Resonance at 4.4 GeV and Additional Structure near 4.1 GeV in e^+e^- Annihilation*

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We observe a resonancelike structure in the total cross section for hadron production by e^+e^- colliding beams at a mass of 4414 ± 7 MeV having a total width $\Gamma = 33 \pm 10$ MeV. From the area under this resonance, we deduce the partial width to electron pairs to be $\Gamma_{ee} = 440 \pm 140$ eV. Further structure of comparable width is present near 4.1 GeV.

In a previous Letter[1] we reported structure in the total cross section σ_T for hadron production by e^+e^- annihilation near the center-of-mass energy $E_{\text{c.m.}} = 4.15$ GeV. The width of that structure appeared to have a typical hadronic value of several hundred MeV, yet the area under it was comparable to the areas under the very narrow resonances $\psi(3095)$[2] and $\psi(3684)$.[3] We report here results from additional measurements of σ_T in the c.m. energy range 3.9 to 4.6 GeV. These data show strong evidence for a new state at 4414 ± 7 MeV having a total decay width of approximately