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FOUR-QUARK MODEL FOR CHARM STATES*†

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ABSTRACT

A recently proposed four-quark mechanism is shown to generate the charm spectroscopy and explain many features of the data. The model implies an η_c degenerate with $\chi(3415)$ and a number of new effects.

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Recently, I proposed that the observed spectrum of meson states does not arise from orbital and radial excitations of the $q\bar{q}$ system, but is rather due to a specific mechanism involving four quarks $(q\bar{q}q\bar{q})$.[1] I thus assumed that direct (s-wave, spin-dependent) $q\bar{q}$ forces are responsible only for the ground state 0^-, 1^- nonets, whereas excitations require (at least) four-quark configurations satisfying certain conditions (described below). This postulate leads both to a very simple mass formula, and to a set of rules for deducing the associated quantum numbers (I, J^{PC}). In fact, this prescription generates virtually the entire known spectrum of (non-charm) meson states to remarkable accuracy, without free parameters. In view of the striking success of this proposal, the present paper is prompted by the following considerations: (1) does the mechanism exhibit the global character one expects of a fundamental theory and work equally well for configurations involving c quarks? (2) if so, the quality and detail of the non-charm results suggest that predictions for new effects in the charm sector should be given serious experimental attention.

At present, the known charm spectroscopy does not afford the wealth of detail found in the non-charm states, and hence a number of alternative theories can presumably be adjusted to fit the data. Nevertheless, the results presented below are impressive in several respects. In the first place, assuming only a value for the η_c mass, excellent predictions are generated for the χ_i states and the ψ excitations $(\psi', \psi'', \ldots)$. Secondly, the model accounts very nicely for such facts as the prevalence of $\psi' \rightarrow \pi\pi\psi$ and $\psi' \rightarrow \eta\psi$ decays, and the association of $\psi(3770)$, $\psi(4030)$, $\psi(4415)$ with $D\bar{D}$, $D^*\bar{D}^*$, $F^*\bar{F}^*$ decay modes, respectively. Also, the interpretation of $\chi(3445)$ and the predicted location of η_c (current enigmas) are consistent with existing data. Thus, these results provide additional strong evidence for the proposed mechanism. Experimental confirmation of the η_c and/or predicted new states would make the case rather compelling.

The relevant 4-quark configuration is shown in Fig. 1a, which we regard as arising from the excitation of an original 2-quark state $(q_1,\bar{q}_2)$ Given a source of energy, an additional pair $(\bar{q}_3 q_4)$ is created; the requisite energy will clearly be minimal if $\bar{q}_3, q_4$ are relatively at rest. Assuming that the extremely strong forces responsible for confinement will attempt to force as many $q\bar{q}$ pairs as possible into the unique energy levels observed in the 0^-, 1^- states, we expect the favored excitations to correspond to the pairs $(q_1\bar{q}_3)$, $(\bar{q}_2 q_4)$, and $(q_1\bar{q}_2)$ forming meson states a, b, and c, respectively. Applying the conditions $(p_1 + p_3)^2 = m_a^2$, etc., to the 4-body system, it is easy to derive the expression

$$M^2 = m_c^2 + 2\left(m_a^2 - m_{q_1}^2\right) + 2\left(m_b^2 - m_{q_2}^2\right) \tag{1}$$

for the mass M of the excited state, where m_{q_i} is the mass of quark q_i.

The underlying physics and some historical background for this mechanism are discussed in Ref. 1; here I simply quote the principal results. The isospin of the system is identical to that of particle c $(I = I_c)$. The parity P is $(-)^L P_a P_b$, where L is the relative angular momentum of mesons a and b. For neutral states, charge conjugation $C = (-)^L$; the g-parity is thus $g = (-)^{L+I}$. It is assumed that the particular combination of a and b is only important if their quantum numbers allow them to be emitted as actual decay products (thresholds permitting); this implies the constraint $g = g_a g_b$. From our identification of a, b, c as either vectors or pseudoscalars, we determine the orientation of the individual quark spins, and hence the most probable value for the total spin S of the system. Given L and S, of course, we severely limit the total angular momentum J. Finally, it is natural to assume that the purely pseudoscalar combinations a, b, c with L = 0 generate the lowest-lying excitations ($J^{PC} = 0^{++}$), and that successively replacing each with a vector leads (in general) to a state of higher J. For I = 1 and I = 1/2, I demonstrated that these rules lead to an almost totally unambiguous classification of states. For I = 0, the situation is more complicated, especially in view of the different types of octet-singlet mixing evident in the 0^-, 1^- states, but one may be guided in most cases by the I = 1, 1/2 members of the corresponding J^{PC} nonet.

It is useful to employ the notation (ab)c for the particles involved. As shown in Ref. 1, the sequence $(\pi\pi)\rho$, $(\rho\pi)\pi$, $(\rho\pi)\rho$, $(\rho\rho)\pi$ and $(\rho\rho)\rho$ generates the ρ, A_1, A_2, ρ' and g mesons, provided the common mass of the u and d quarks is taken to be m_π. A similar sequence generates the I = 1/2 states if $m_s = m_K$. Whether these are actual or effective quark masses is not a question I will pursue here; for the purposes of this mechanism, they are the only acceptable values. In order to determine the mass of the c quark, we consider the diagram in which $q_1 = c$, q_2 = (u or d), and $q_3 = q_4$ = (u or d). The configuration $(D\pi)D^*$ with L = 1 corresponds to the decay mode of the D^*, and Eq. (1) implies that $M^2 = m_{D^*}^2 + 2\left(m_D^2 - m_c^2\right)$; thus $M = m_{D^*}$ if $m_c = m_D$. (At the level of this argument, it suffices to take these masses from the charged states π^+, K^+, D^+.) Given the ψ, D, D^* masses (and using the values for m_F, m_{F^*} indicated by a recent experiment),[2] the only input yet to be determined is the mass of the $c\bar{c}$ 0^{-+} state (the η_c). Below I postulate a value for η_c in order to generate $\chi(3415)$, $\chi(3510)$ and $\psi'(3686)$.

Let us first, however, consider those 4-quark configurations for which M depends neither on m_c nor on m_{η_c}. We thus take $\bar{q}_3 q_4 = c\bar{c}$, and choose q_1, q_2 from among u, d, s. Experimentally, the vector (1^{--}) states are of particular interest, since they produce clear signals in e^+e^- annihilation. In Ref. 1, the vector excitation ρ' was identified with $(\rho\rho)\pi$ (L = 1); here we calculate $(D^*\bar{D}^*)$PS and $(F^*\bar{F}^*)$PS, where PS = π, η, η', etc. The state of lowest mass is generated by $(D^*\bar{D}^*)\pi$, yielding M = 4010 MeV, I = 1; this is almost degenerate with the I = 0 state $(D^*\bar{D}^*)\eta$, which has M = 4044. It is reasonable to identify both of these states with $\psi(4030)$, especially in view of its propensity to decay into $D^*\bar{D}^*$.[3] In fact, the latter property is in serious disagreement with simple estimates from $c\bar{c}$ models, and has led previous authors to suggest that $\psi(4030)$ is a 4-quark state.[4] As they note, a possible objection to this interpretation is the apparent absence of the decay mode $\psi(4030) \to \psi$ + anything. In this model, however, there is an argument to justify this suppression. Thus, the $c\bar{c}$ pair has total spin S = 0, and hence a ψ decay would require a spin-flip to occur.

Replacing D^* by F^* and/or η by η' generates additional I = 0 vector states listed in Table I; I have also employed an I = 0 pseudoscalar predicted in Ref. 1 and (tentatively) identified with $X_0(1430)$.[5] There is, moreover, yet another type of configuration which may produce vectors. The principal ambiguity in the J^{PC} classification scheme involves states such as $(K\bar{K})\rho$, which may be either 0^{++} or 1^{--}, according to whether L = 0 or 1. In the case of $(\pi\pi)\omega$ the g-parity argument selects L = 0, and hence it is classified as a 0^{++} state degenerate in mass with the ω. Experimentally, there is some evidence to support this prediction in the I = 0

$\pi\pi$ system.[6] On the other hand, $(K\bar{K})\rho$ lies some 400 MeV above the ρ, and taking L = 1 would permit identification with a possible ρ' in the 1200 MeV region.[5] Assuming this to be true for the (much larger) $c\bar{c}$ excitation, I have included four additional states in Table I. With regard to this table, I note the following: (1) The configurations $(D\bar{D})\rho$ and $(D\bar{D})\omega$ lead to almost exactly degenerate I = 0 and I = 1 vectors just above 3.8 GeV; the identification with $\psi''(3770)$ is consistent with the dominant decay $\psi'' \to D\bar{D}$.[5] (2) Peaks corresponding to the effects predicted at 3972 and 4120 are visible in the SPEAR data.[7] (3) $\psi(4415)$ is, in fact, the source of the F,F* mesons reported in the literature, and its association with $(F^*\bar{F}^*)X_0$ is entirely consistent with a prominent (possibly dominant) $F^*\bar{F}^*$ decay.[2] In view of the errors presently quoted for m_F, m_{F^*}, I have taken $m_{F^*} = 2140$ as given, and chosen m_F such that $m_{F^*}^2 - m_F^2 = m_{D^*}^2 - m_D^2$ in constructing these tables. This yields $m_F = 2006$ (as compared to $m_F = 2030 \pm 60$). (4) The three states predicted in the 4.2 - 4.3 GeV region have not been seen, although $(F^*\bar{F}^*)\eta$ and $(F^*\bar{F}^*)\eta'$ could both be quite narrow if $2m_{F^*} > 4290$. There is no obvious excuse for the absence of $(D^*\bar{D}^*)X_0$, but one experiment exhibits at least a hint of such a state at the right mass (4.25 GeV).[7]

Other choices for a, b, c yield 0^{++}, 1^{++} partners for these vectors which are listed in Table II; also, $(D^*\bar{D})\omega$ and $(F^*\bar{F})\phi$ give 2^{++} states at 3947 and 4174 MeV, respectively. However, in order to generate states below 3.7 GeV, it is necessary to consider the class of configurations in which $q_1\bar{q}_2 = c\bar{c}$, and $q_3 = q_4 =$ (u, d, or s). Here meson c is either the ψ or η_c, and hence we must come to some decision regarding the latter. It has been suggested that the state X(2830) seen in $\psi \to \gamma X$, and/or

$\chi(3445)$ are pseudoscalars; e.g., η_c and η'_c.[8] The existing experimental evidence is, if anything, somewhat negative.[9] In the present scheme, a quick trial indicates that X cannot be identified with η_c, since the resulting spectrum cannot be reconciled with the data (the ψ' and χ states). In this treatment, the ψ' has been used to decide the issue. Thus, $(D\bar{D})\psi$ and $(F\bar{F})\psi$ are relatively low mass excitations of the ψ, and are hence identified as 0^{++} states. The only chance to generate the ψ' is via $(D^*\bar{D}^*)\eta_c$, which implies that $m_{\eta_c} = 3380$ MeV (in order to produce $M = m_{\psi'} = 3686$). I therefore suggest that there is but one pseudoscalar (η_c), lying some 300 MeV above the ψ. Although this may appear bizarre in the context of some potential models, there is no fundamental reason to reject such a possibility. Indeed, the mass of the other singlet pseudoscalar (η') is known to be anomalously high (from the standpoint of simple models), and the singlet partners ω,η' exhibit just such a pattern.

Given this assumption, it is straightforward to generate the spectrum listed in Table III. It is important to note the following points: (1) ψ' lies below the $D\bar{D}$ threshold, and hence has two options for decay which do not involve $c\bar{c}$ annihilation (suppressed by the OZI rule). In the first case, ψ' may decay to one of the lower states given in Table III by emitting a photon. This requires a change in S and/or L while maintaining the 4-quark structure. However, ψ' may also decay strongly by dissociating into ψ + hadrons. In this model these are not OZI-suppressed, and one expects $\psi' \to \pi\pi\psi$ and $\psi' \to \psi\eta$ given the available phase space. Experimentally, this is precisely what happens ($\psi' \to \psi\eta$ is a source of difficulty for charmonium models).[5,10] I note also that there is virtually zero phase space for $\psi' \to \pi\pi\eta_c$; for a lower mass η_c one would expect (unobserved) decays of the type $\psi' \to \eta_c$ + hadrons. (2) Radiative decays of $\psi' = (D^*\bar{D}^*)\eta_c$ to $(F\bar{F})\psi$ and $(F^*\bar{F})\psi$ are not OZI-suppressed, since the (virtual) transition $D^*\bar{D}^* \to F^*\bar{F}^*$ is allowed via Fig. 1b. One would, however, expect some inhibition of the rate from this intermediate step. Decays involving more than one spin-flip should be comparably disfavored. On this basis, the transition $\psi' \to (F\bar{F})\psi$ is the least likely, whereas $(F\bar{F})\psi \to \gamma\psi$ involves no spin flips and is uniquely favored. Therefore, in identifying $(F\bar{F})\psi$ with $\chi(3445)$, one may readily understand the (relative) absence of a signal in $\psi' \to \gamma\chi$, despite its presence in $\psi' \to \gamma(\gamma\psi)$.[8] (3) Predictions for the well-established χ states (3415, 3510, 3555) are in good agreement, both for the masses and the favored J^{PC} values.[5,8] This model implies that the η_c is degenerate in mass with $\chi(3415)$, and hence accounts for some of the events attributed to that state. (4) With regard to the two states predicted below 3.3 GeV, I claim that the 2^{++} level at 3268 has already been seen; i.e., it lies in the kinematic reflection of $\chi(3510)$ in $\psi' \to \gamma(\gamma\psi)$ and causes it to appear uncharacteristically broad.[8] Finally, the 0^{++} level degenerate with ψ cannot appear in $\psi' \to \gamma(\gamma\psi)$. It should, however, appear at some level in $\psi' \to \gamma$ + hadrons.

In summary, it seems clear that the model does remarkably well for a theory without adjustable parameters, and provides a unified description of the meson spectroscopy (charm and non-charm). A variety of strong predictions involving the η_c, $\chi(3445)$, and states below 3.3 GeV will provide stringent additional tests.[11] I also note that vector states of the type $c\bar{c}c\bar{c}$ are anticipated at 5.99, 6.43, 6.73 and 7.20 GeV, and 1^{++}, 2^{++} excitations of the D are predicted at 2.34 and 2.46 GeV, respectively.

REFERENCES AND FOOTNOTES

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6. In particular, I note the $(\pi^+\pi^-)$ peak observed in $\psi \to \phi\pi^+\pi^-$; see G. J. Feldman, SLAC Report SLAC-198 (November 1976).

7. See detail of R in the 3.6 - 4.6 GeV region reported by P. A. Rapidis *et al.*, Phys. Rev. Lett. **39**, 526 (1977).

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11. Another possibility would be to detect monochromatic charged pions in the decays of $\psi(4030)$ and $\psi(4415)$ to the $I = 1$ component of $\psi(3770)$; these correspond to $E = 222$ and 571 MeV, respectively, in the C.M.

TABLE I

Predicted Vector States vs Experiment[5,7]

Type (ab)c	Mass (MeV)	Experiment
$(D^*\bar{D}^*)\eta_c$	3686	$\psi'(3686)$
$(D\bar{D})\rho$ (I = 1)	3804	$\psi(3770)$
$(D\bar{D})\omega$	3806	
$(F^*\bar{F}^*)\eta_c$	3972	Peak in R
$(D^*\bar{D}^*)\pi$ (I = 1)	4010	
$(F\bar{F})\phi$	4039	$\psi(4030)$
$(D^*\bar{D}^*)\eta$	4044	
$(D^*\bar{D}^*)\eta'$	4120	Peak in R
$(F^*\bar{F}^*)\eta$	4218	-
$(D^*\bar{D}^*)X_0$	4254	-
$(F^*\bar{F}^*)\eta'$	4291	-
$(F^*\bar{F}^*)X_0$	4421	$\psi(4415)$

TABLE II

Predicted 0^{++}, 1^{++} States with Mass $\geq m_{\psi'}$

0^{++} (L = 0, S = 0)		1^{++} (L = 0, S = 1)	
Type (ab)c	Mass (MeV)	Type (ab)c	Mass (MeV)
$(F\bar{F})\eta_c$	3682	$(F^*\bar{F})\eta_c$	3830
$(D\bar{D})\pi$ (I=1)	3728	$(D^*\bar{D})\pi$ (I=1)	3871
$(D\bar{D})\eta$	3766	$(D^*\bar{D})\eta$	3908
$(D\bar{D})\eta'$	3846	$(D^*\bar{D})\eta'$	3985
$(F\bar{F})\eta$	3946	$(F^*\bar{F})\eta$	4106
$(D\bar{D})X_0$	3990	$(D^*\bar{D})X_0$	4124
$(F\bar{F})\eta'$	4024	$(F^*\bar{F})\eta'$	4151
$(F\bar{F})X_0$	4162	$(F^*\bar{F})X_0$	4293

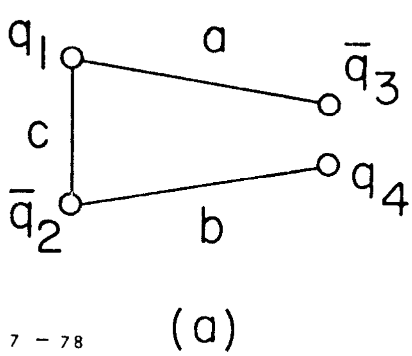
TABLE III

Predicted Charm Spectrum with Mass $\leq m_{\psi'}$ vs Experiment[5,8]

Type (ab)c	L, S	J^{PC}	Mass (MeV)	Experiment
$(D^*\bar{D}^*)\eta_c$	1, 0	1^{--}	3686	$\psi'(3686)$
$(F^*\bar{F})\psi$	2, 1	2^{++}	3583	$\chi(3555)$
$(D^*\bar{D})\eta_c$	0, 1	1^{++}	3536	$\chi(3510)$
$(F\bar{F})\psi$	0, 0	0^{++}	3425	$\chi(3445)$
$(D\bar{D})\eta_c$	0, 0	0^{++}	3380	$\chi(3415)$
$(D^*\bar{D})\psi$	2, 1	2^{++}	3268	-
$(D\bar{D})\psi$	0, 0	0^{++}	3097	-

FIGURE CAPTION

Fig. 1. (a) Four-quark system with pairs forming mesons a, b, and c. The pair $\bar{q}_3 q_4$ are relatively at rest. (b) Diagram illustrating the OZI-allowed transition $D^*\bar{D}^* \to F^*\bar{F}^*$.



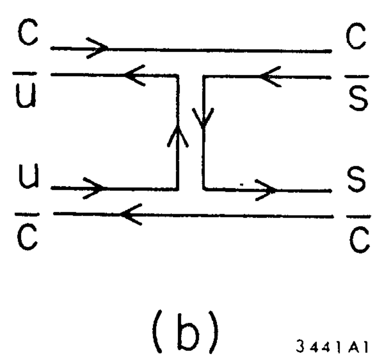


Fig. 1