Rumsfeld Hadrons

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Donald Rumsfeld, in attempting to excuse the inexcusable, once (in)famously said that "there are things that we know we know; there are things that we know we don't know; and then there are things that we don't know that we don't know". Recent discoveries about hadrons with heavy flavours fall into those categories. It is of course the third category that is the most tantalising, but lessons from the first two may help resolve the third.

arXiv:0706.2709v1 [hep-ph] 19 Jun 2007

I. THINGS THAT WE KNOW WE KNOW

We have heard reported observation of the B_c with mass $m(B_c) = 6276.5 \pm 4.0 \pm 2.7$MeV and comparison of its mass with predictions from various models and lattice QCD[1]. Not everything is mysterious. Compare this lightest $b\bar{c}$ with $(m(\psi) + m(\Upsilon))/2 = 6278.6$. They agree to better than a part per mille. This illustrates how apparent agreements with the mass are driven by the large intrinsic mass scales of the b and c and that yet again the mass scales of hadrons are phenomenologically rather straightforward. The interesting dynamics will come when excitations of the $b\bar{c}$ are found.

A more profound testing of QCD effects has come from the discovery of Σ_b and Σ_b^* at CDF[2]. The chromomagnetic splittings between baryons were predicted thirty years ago[3]. The $\Delta - N$ splitting of 300MeV involves gluon exchange among all three constituent flavours. If one of these were replaced by an infinitely massive flavour, its contribution to the colour magnetism would vanish as magnetic couplings are inversely proportional to mass. The spin couplings of the two light flavours then leave a residual splitting of 200MeV between the light Λ_Q and the (degenerate) Σ_Q and Σ_Q^*.

In reality we dont have infinitely massive flavours but can compare the trend as Q is in turn s, c, b [4]. The $\Sigma - \Lambda$ separation grows while the $\Sigma - \Sigma^*$ come together. The trend is well known for strange and charm; the CDF results for bottom confirm this beautifully. Although we do not fully understand what the degrees of freedom that we call "constituent quarks" are, nonetheless, they behave in a remarkably simple fashion. It remains a challenge to theory to explain why. (See also [5] for extensive discussion about this area).

The area that is phenomenologically understood extends to mesons where the $q\bar{q}$ are in relative $L = 0$. In the recent past there has been much new information about the $c\bar{s}$ states. The predictions and observations are consistent for the $0^-; 1^-$ states (for an up to date comparison see [6, 7]).

BaBar recently announced the discovery of a new D_s state seen in e^+e^- collisions decaying to D^0K^+ or $D^+K_S^0$[8]. The Breit-Wigner mass of the new state is

$$M(D_{sJ}(2860)) = 2856.6 \pm 1.5 \pm 5.0 \text{ Mev} \quad (1)$$

and the width is

$$\Gamma(D_{sJ}(2860)) = 48 \pm 7 \pm 10 \text{ MeV}. \quad (2)$$

There is no evidence of the $D_{sJ}(2860)$ in the D^*K decay mode[8] or the $D_s\eta$ mode. There is, furthermore, structure in the DK channel near 2700 MeV that yields Breit-Wigner parameters of

$$M(D_{sJ}(2690)) = 2688 \pm 4 \pm 2 \text{ MeV} \quad (3)$$

and

$$\Gamma(D_{sJ}(2690)) = 112 \pm 7 \pm 36 \text{ MeV}. \quad (4)$$

The state $D_s(2690)$ has the characteristics of a vector and is consistent with being the $2S(^3S_1)$ or possibly mixed with $^3D_1$. Ref[6] discusses this in more detail. If this is true, then a test is to produce the state in B decays.

The production of the radially excited D_{s0} in B decays can be estimated with the ISGW formalism[9]. Since vector and scalar $c\bar{s}$ states can be produced directly from the W current, the decays $B \rightarrow D_s^*(2S)D_{(J)}$ or $D_{s0}(2P)D_{(J)}$ serve as a viable source excited D_s states. Computationally, the only differences from ground state D_s production are kinematics and the excited D_s form factors. The relative rates for excited vector production were given in Ref. [6, 10]:

$$B \rightarrow D_s^*\bar{D} : B \rightarrow D_s^*(2S)\bar{D} \approx 1 : 0.3 - 0.7. \quad (5)$$

In the $L = 1$ sector the model predicts the radial excitation $2P(^3P_0)$ at 2820. The observation of $D_{sJ}(2860)$ is consistent with this though higher spin 3^- has also been suggested[11]. Angular distributions can sort this out. If it is 0^+ then some interesting further tests can ensue which touch on the next level of conundrum:

II. THINGS THAT WE KNOW WE DONT KNOW

In the $L = 1$ $c\bar{s}$ sector, why are the masses of $0^+(2317)$ and $1^+(2460)$ so much lower than the models had expected? I have always felt that this is an example of where the naive quark model is too naive; for details see my summary talk in Hadron03[12]. When a $q\bar{q}$ state occurs in $L = 1$, but can couple to hadron pairs in S-wave, the latter will distort the underlying $q\bar{q}$ picture. The $c\bar{s}$ 0^+ state predicted above DK threshold couples to the DK continuum. This mixes DK into the wavefunction, and leads to a weakly bound quasi-molecular state just below DK threshold. Analogous dynamics was predicted also for the 1^+ coupling to D^*K. This effectively "unquenches" the quark model for such states and led to the molecular picture of [13]. This has been discussed extensively and the effects of the intrinsic $c\bar{s}$ seed also investigated in [14].

There has also been suggestion that this is an effect of chiral symmetry[15], the $0^- - 1^-$ states with 143 MeV mass gap matching their $0^+ - 1^+$ chiral partners with 146MeV. This is intriguing but among things that I don't undertstand are: (i) why does this apply for $c\bar{s}$ where no manifestly light flavours are involved rather than $c\bar{u}$ or $c\bar{d}$; (ii) which of the two 1^+ states is the comparison supposed to be made with? (In the infinitely massive quark limit there is a clear answer, but it is trivial as the splittings go to zero; for finite masses there is mixing between the $S = 0, 1$ basis and the $p_{1/2} - p_{3/2}$ states and the comparison is non-trivial).

The full spin-dependent structure expected at order α_s^2 in QCD has been computed by Pantaleone *et al.*[16] and reveals that an additional spin-orbit contribution to the spin-dependent interaction exists when quark masses are not equal. When these are incorporated in a constituent quark model there can be significant mass shifts leading to a lowered mass for the D_{s0} consistent with the $D_{s0}(2317)$[17]. The identification of analogue states with bottom flavour could help decide among these pictures.

If both the 2860 and 2317 are canonical $c\bar{s}$ 0^+ states in $2P$ and $1P$ respectively, then their relative production in B-decays should be[10]:

$$B \to D_s(2860)\bar{D} : B \to D_s(2317)\bar{D} \approx 1 : 0.6 - 1.8. \tag{6}$$

A comparison in B-decays is warranted.

III. THINGS THAT WE DON'T KNOW WE DON'T KNOW

There is much unexpected activity showing up in the charmonium sector: $X(3940)$ seen in $\psi\omega$ [18], $Y(3940)$ seen in $D^*\bar{D}$ [19], $\chi_{c2}(3930)$ [20] and $Y(4260)$ [21]. (The inclusion of charge-conjugated reactions is implied throughout.) Furthermore there are also three prominent enhancements X in $e^+e^- \to \psi + X$ [19], which are consistent with being the η_c, η_c' and χ_0.

In $e^+e^- \to \psi + X$ there is no sign of the $X(3872)$; this state now appears to have $C = +$ and be consistent with 1^{++} [22]. This J^{PC} was first suggested in Ref. [23] and a dynamical picture of it as a quasi-molecular $D^{*0}\bar{D}^0$ state discussed in Refs. [23, 24]. The suppression of this state among prominent $C = +$ charmonium states [19] may thus be consistent with its molecular versus simple $c\bar{c}$ nature.

Why the χ_0 is prominent in $e^+e^- \to \psi + X$ and the χ_2 not is one question (contrast with light flavours where $e^+e^- \to \omega f_2$ is clearly seen, in particular in ψ decay). The nature of the structure $X(3940)$ is clearly another question. On mass grounds it could contain radially excited χ states; but if so why does it not appear in $D\bar{D}$? (If χ_0 is prominent in the data on $e^+e^- \to \psi + X$, then if $2P$ states are strongly produced, one would expect 2P(χ_0) also to be significant.) Given that $\eta_c(2S)$ is prominent, then perhaps $\eta_c(3S)$ is also, which would explain the suppressed $D\bar{D}$. A third possibility is that hybrid charmonium with C=+ is being produced, which also is predicted not to decay to $D\bar{D}$.

There is a folklore that $X(3940)$ is too light to be hybrid charmonium, but I disagree with that. Lattice QCD and flux tube models agree that the typical mass scale for an exotic 1^{-+} is ~4.2 GeV[25, 26]; given that spin-dependent splittings place a 0^{-+} lighter than this and 1^{--} slightly heavier[27], it is quite plausible that a 0^{-+} hybrid (mixing with $\eta_c(3S)$?!) is in this region, and that the vector $Y(4260)$ is also part of this story. Proving this will be hard though; I shall return to this later.

First let's consider the lightest of the novel charmonium states, the $X(3872)$ at D^0D^{*0} threshold and which is almost certainly an axial meson. This has been known for some time and is generally agreed to have a tetraquark affinity; whether it is a genuine D^0D^{*0} molecule or a compact $cuc\bar{u}$ is a more subtle issue. If the quark-pairs are tightly clustered into diquarks, then a $S = 0$ and $S = 1$ are required to make the 1^{++}. Consequently other states, combinations of $0^+ - 0^+$ and $1^+ - 1^+$ would be expected. The absence of such a rich spectrum suggests that the overriding dynamics is that the constituents rearrange into loosely bound colour singlet $c\bar{u}$-$u\bar{c}$, or D^0D^{*0}. I don't plan to discuss that today but would raise a couple of points about the binding mechanism that seem not to have been widely considered.

There is a significant possibility that this state and the "conventional" $\chi_1(3500)$ may have some mixing. If so there will be some isospin breaking in the latter's decays such that $br(\chi_1 \to K^+K^-\pi) > br(K^0\bar{K}^0\pi)$.

It is the dynamical origin of this state that concerns me more. The arguments for it being a molecule were discussed in ref[28] and π exchange as a binding mechanism was also considered. Tornqvist had earlier suggested that a whole series of hadrons might form such "deuson" states via π exchange[29]. Swanson[24] considered a quark exchange model, in which the coincidence of DD^* and $\psi\omega$ as well as $\psi\rho$ energies played a role. Swanson found an attractive force but also showed that, within the approximations employed, this was insufficient to bind and he had to include π exchange to do so; as such this effectively recovers Tornqvist's π-exchange model and leaves quark-interchange having little to do with the binding. There is one comment however: Swanson considered only short distance (contact) gluon exchange in his quark exchange calculation and not the contribution of the tensor force that gluons also induce. Note that the Yukawa π exchange potential also is not sufficient to bind; it is the tensor force that is found to be essential[24, 29]. So it would be interesting to see what happens if the tensor contribution from gluon exchange is also included; this is being investigated by C Thomas[30]. Understanding this may also have implications for other anomalous charmonium states. It would also have potential implications for the presence or absence of analogous states involving heavy flavours, and also for $D_sD_s^*$: this would receive no contribution from π exchange, and η exchange is expected to be negligible whereas quark-interchange could occur. Furthermore, π exchange can also occur between D and D^* (i.e with no $\bar{D}$ [29]) whereas quark exchange would not link to the $\psi\omega$ and the effects would generally differ.

I now turn to hybrid charmonium and evaluate the prospects that it is being exposed. There are three states of interest (i) $X(3940)$ in the recoil spectrum $e^+e^- \to \psi + X(3940)$, which is not seen in $\omega\psi$; (ii) $Y(3940)$ seen in B-decay and which is seen in $\omega\psi$; (iii) $Y(4260)$ which is 1^{--} in $e^+e^- \to \psi\pi\pi$, with no observed decay into $D\bar{D}$. The fact that there is no sign of established 3S/2D(4040/4160) 4S(4400) in the $\psi\pi\pi$ data already marks this state as anomalous and eliminates conventional explanations as potential states are already apparently occupied. The mass, large width into $\psi\pi\pi$, small leptonic width ($O(5-80)$eV, contrast O(keV) for known states), affinity for DD_1 threshold and apparent decay into $\psi\sigma$ or $\psi f_0(980)$ are all consistent with predictions made for hybrid vector charmonium[31]. I now assess the empirical status of hybrid charmonium and other possible interpretations of the states.

The eight low-lying hybrid charmonium states ($c\bar{c}g$) were predicted in the flux-tube model to occur at $4.1 - 4.2$ GeV [26], and in UKQCD's quenched lattice QCD calculation with infinitely heavy quarks to be 4.04 ± 0.03 GeV (with un-quenching estimated to raise the mass by 0.15 GeV) [25]. The splittings of $c\bar{c}g$ from the above spin-average were predicted model-dependently for long distance (Thomas precession) interactions in the flux-tube model [32], and for short distance (vector-one-gluon-exchange) interactions in cavity QCD [27, 33]. For the 1^{--} state the long and short distance splittings respectively are 0 MeV and 60 MeV. Long ago the spin-dependent mass shifts were calculated in cavity QCD, though the resulting pattern is expected to be more generally true[27, 34]. Quenched lattice QCD indicates that the $c\bar{c}g$ 1^{--}, $(0,1,2)^{-+}$ are less massive than 1^{++}, $(0,1,2)^{+-}$ [43]. The spin splitting for this lower set of hybrids in quenched lattice NRQCD is $0^{-+} < 1^{-+} < 1^{--} < 2^{-+}$ [34], at least for $b\bar{b}g$. This agrees with the ordering found in the model-dependent calculations for $q\bar{q}g$ [27] in the specific case of $c\bar{c}g$ [32, 33]. For $b\bar{b}g$ lattice QCD predict substantial splittings ~ 100 MeV or greater [34], which become even larger in the model-dependent calculations for $c\bar{c}g$ [32, 33].

Thus the consensus is that the resulting pattern is, in decreasing mass, $1^{--}; 1^{-+}; 0^{-+}$ with the mass gap between each state being the same and of the order of 10-100MeV. Thus theory strongly indicates that if $Y(4260)$ is $c\bar{c}g$, and the splittings are not due to mixing or coupled channel effects, then the J^{PC} exotic 1^{-+} and non-exotic 0^{-+} $c\bar{c}g$ are below $D^{**}\bar{D}$ threshold, making them narrow by virtue of the selection rules. The 1^{-+} decay modes [40] and branching ratios [41] have extensively been discussed. Thus it is consistent to identify possible states as $1^{--}(4.25); 1^{-+}(4.1); 0^{-+}(3.9)$ and to speculate whether there are two states $1^{-+}(4.1); 0^{-+}(3.9)$ in either the $X/Y(3940)$ structures of Belle or e^+e^-. This is clearly a question that statistics from a super-B factory may resolve for the B-decays or $e^+e^- \to \psi + X$.

Mass arguments alone will not be convincing; we need to understand the dynamics of production and decay and show that these fit best with hybrid states.

A lattice inspired flux-tube model showed that the decays of hybrid mesons, at least with exotic J^{PC}, are suppressed to pairs of ground state conventional mesons [35, 36]. This was extended to all J^{PC}, for light or heavy flavours in Ref. [37]. A similar selection rule was found in constituent gluon models [38], and their common quark model origin is now understood [39]. It was further shown that these selection rules for light flavoured hybrids are only approximate, but that they become very strong for $c\bar{c}$ [33, 37]. This implied that decays into $D\bar{D}$, $D_s\bar{D}_s$, $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ are essentially zero while $D^*\bar{D}$ and $D_s^*\bar{D}_s$ are very small, and that $D^{**}\bar{D}$, if above threshold, would dominate. (P-wave charmonia are denoted by D^{**}). As $c\bar{c}g$ is predicted around the vicinity of $D^{**}\bar{D}$ threshold, the opportunity for anomalous branching ratios in these different classes was proposed as a sharp signature [26, 37]. (To the best of our knowledge Ref. [37] was the first paper to propose such a distinctive signature for hybrid charmonium.)

It has become increasingly clear recently that there is an affinity for states that couple in S-wave to hadrons, to be attracted to the threshold for such channels [12]. The hybrid candidate 1^{--} appearing at the S-wave $D_1(2420)\bar{D}$ is thus interesting.

More recently the signatures for hybrid charmonia were expanded to note the critical region around $D^{**}\bar{D}$ threshold as a divide between narrow states with sizable branching ratio into $c\bar{c}$ + light hadrons and those above where the anomalous branching ratios would be the characteristic feature [40, 41]. Here widths of order 10 MeV were anticipated around the threshold. It was suggested to look in e^+e^- annihilation in the region immediately above charm threshold for state(s) showing such anomalous branching ratios [41]. The leptonic couplings to e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ were expected to be suppressed [42] (smaller than radial S-wave $c\bar{c}$ but larger than D-wave $c\bar{c}$, but with some inhibition due to the fact that in hybrid vector mesons spins are coupled to the $S = 0$, whose coupling to the photon is disfavoured [41]).

The dominant mode would be to DD_1 or D^*D_0 if kinematically allowed; these being S-wave and near threshold, with low recoil momentum, there can be a significant amplitude for their constituents to rearrange leading to the kinematically allowed decay channels $\psi\pi\pi$ including $\psi f_0/\sigma$. This would then be the explanation of the strong decay width to $\psi\pi\pi$, which would otherwise superficially be OZI suppressed.

There are several of the theoretical expectations already given for $c\bar{c}g$ that are born out by $Y(4260)$: (1) Its mass is tantalizingly close to the prediction for the lightest hybrid charmonia; (2) The expectation that the e^+e^- width should be smaller than for S-wave $c\bar{c}$ is consistent with the data[31]; (3) The predicted affinity of hybrids to $D^{**}\bar{D}$ could be related to the appearance of the state near the $D^{**}\bar{D}$ threshold. The formation of $D^{**}\bar{D}$ at rest may lead to significant re-scattering into $\psi\pi^+\pi^-$, which would feed the large signal.

The nearness of $Y(4260)$ to the $D_1(2420)\bar{D}$ threshold, and to the $D_1'\bar{D}$ threshold, with the broad D_1' found at a mass of ~ 2427 MeV and width ~ 384 MeV [44], indicate that these states are formed at rest. Also, these are the lowest open charm thresholds that can couple to 1^{--} in S-wave (together with $D_0\bar{D}^*$, where the D_0 mass ~ 2308 MeV and width ~ 276 MeV [44]). Flux-tube model predictions are that the D-wave couplings of 1^{--} $c\bar{c}g$ to the 1^+ and 2^+ D^{**} are small [33, 37, 45]; and there is disagreement between various versions of the model on whether the S-wave couplings to the two 1^+ states are large. If these couplings are in fact substantial, the nearness of $Y(4260)$ to the thresholds may not be coincidental, because coupled channel effects could shift the mass of the states nearer to a threshold that it strongly couples to; and it would experience a corresponding enhancement in its wave function. The broadness of $Y(4260)$ also implies that its decay to $D_1(2420)\bar{D}$, $D_1'\bar{D}$ and $D_0(2308)\bar{D}^*$ which feed down to $D^*\bar{D}\pi$ and $D\bar{D}\pi$ [6] would be allowed by phase space and should be searched for to ascertain a significant coupling to D^{**}.

Flux-tube model width predictions for other charm modes are 1 − 8 MeV for $D^*\bar{D}$ [45], with $D\bar{D}$, $D_s\bar{D}_s$, $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ even more suppressed. Thus a small $D\bar{D}$ and $D_s\bar{D}_s$ mode could single out the hybrid interpretation. Unless there is significant rescattering from $\psi f_0(980)$, the hybrid decay pattern is very different from the $c\bar{s}s\bar{c}$ four-quark interpretation for $Y(4260)$ which decays predominantly in $D_s\bar{D}_s$ [46]. Thus data on the latter channel, or limit on its coupling, could be a significant discriminator for the nature of this $Y(4260)$.

The data[47] on $e^+e^- \rightarrow D_s\bar{D}_s$ show a peaking above threshold around 4 GeV but no evidence of affinity for a structure at 4.26GeV. This is suggestive but needs better quantification. If these data are confirmed, then as well as ruling out a $cs\bar{c}\bar{s}$ at this mass, they will also add support to the hybrid interpretation. The same data also show there is no significant coupling of $Y(4260)$ to $D\bar{D}$; $D^*\bar{D}$ or $D^*\bar{D}^*$, all of which are in accord with predictions for a hybrid state.

Before finally concluding that the $Y(4260)$ is hybrid charmonium, we must eliminate a third possibility: is the 1^{--} $X(4260)$ an effect of π exchange attraction near the DD_1 threshold? Note that this is the first threshold in e^+e^- annihilation to charm where the charmed mesons emerge in S-wave. This would be analogous to the 1^{++} $X(3872)$ DD^* that we discussed earlier. In the $Y(4260)$ case, π-exchange connects $DD_1 \rightarrow D^*D_0$ and gives attraction in the 1^{--}, $I = 0$ channel (the $Y(4260?)$) and in the 1^{-+} $I = 1$ channel (a truly exotic beast!). There is also the question of whether quark-exchange gives attraction. If so this would potentially allow enhancement near the D_sD_{s1} threshold, whereas neither π-exchange nor s-channel resonances would expect such a structure.

An indirect hint that $Y(4260)$ might be connected to resonant gluonic excitation is that there appears to be an analogous phenomenon in the $s\bar{s}$ sector[48, 49]. The cross section for $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$ has significant contribution from $e^+e^- \rightarrow KK_1$ with rescattering into $\phi\pi\pi$. A resonance with width $\Gamma = 58 \pm 16 \pm 20$MeV with large branching ratio into $\phi\pi\pi$ is seen with mass of 2175MeV[49]. Simple arithmetic shows that the mass gap from this state to $m(\phi)$ is within the errors identical to that between $Y(4260)$ and $m(\psi)$. This is perhaps reasonable if the cost of exciting the gluonic flux-tube is not sensitive to the masses of the $q\bar{q}$ involved (as lattice QCD seems to suggest), in which case a hybrid vector production and decay is consistent with data. The KK_1 and K^*K_0 thresholds do not relate so readily to the 2175 state as do the analogous charm states with the 4260, which makes it less likely perhaps that the 4260 and 2175 can be simply dismissed as non-resonant effects associated with S-wave channels opening. While it may not be possible to prove that these are definitively signals for hybrid vector mesons, all of the phenomena are in accord with expectations for hybrids.

If this 4260 state is not hybrid vector charmonium, then where it is?

Suppose that it is. Where else should we look? Clearly the $[0,1]^{-+}$ states predicted to lie below the $Y(4260)$ become interesting. The properties and search pattern for such states are discussed in ref.[41]. In $e^+e^- \rightarrow \psi + X$ it is possible that such states could feed the signal at 3940MeV. If the production is via strong flux-tube breaking there is a selection rule[50] that suppresses $\psi + X$ when X has negative parity. However, it is possible that the dominant production for $c\bar{c}\ + c\bar{c}$ is by "preformation", where a perturbative gluon creates the second $c\bar{c}$ pair (the highly virtual photon having created the initial pair). In such a case there is no selection rule forbidding $X \equiv [0,1]^{-+}$ hybrids; however, the amplitude will be proportional to the short distance wavefucntion of the hybrid, which is expected to be small compared to those of e.g. $\eta_c(3S)$ though perhaps comparable to those of χ_J. Thus it would be interesting to measure the J^{PC} of the $X(3940)$ region to see if it contains exotic 1^{-+}. If such a signal were found then we could truly be sure that hybrid charmonium had been revealed.

Acknowledgments

This work is supported, in part, by grants from the Particle Physics and Astronomy Research Council, and the EU-TMR program "Eurodice", HPRN-CT-2002-00311.

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