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New Metastable Charmonium and the ψ' Anomaly at CDF

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Abstract

Production of metastable charmonium states more massive than the $\psi(3685)$ is expected in models and could be the source of up to 50% of the ψ observed at large p_T at the Tevatron.Narrow $2^{-+}, 2^{--} c\bar{c}$ are predicted at around 3.8GeV and radially excited $2^3P_{1,2}$ may also have suppressed hadronic widths making these states potentially extra sources of $\psi(3685)$. Colour octet components are believed to dominate ψ production at the Tevatron which suggests that hybrid charmonium production may also be prominent. Estimates of hybrid production rates and branching ratios into charmonium suggest that metastable hybrids with mass $\approx$ 4GeV may play an important role in generating the observed $\psi(3685), \psi(3095)$

1 Introduction

The largest discrepancy between the predictions of the Standard Model and experiment may be the recent measurements of charmonium production at large transverse momentum in $p\bar{p}$ collisions at the Tevatron[1]. The clearest evidence for an anomaly comes from the CDF report of a ψ' production rate that is a factor of about 30 larger than theoretical expectation, too large a discrepancy to be accomodated by tinkering with parameters in the theory and suggestive of a source additional to those so far included in the calculations. Production of the ψ also appears to be enhanced relative to expectations by a factor of 2 or 3 [1]; though smaller than the ψ' enhancement in ratio, this is nonetheless significant and a comparable enhancement in absolute magnitude.

In this letter I bring together recent developments in, at first sight, rather unrelated areas of theory and experiment and show how they may provide a consistent picture including a possible explanation of the charmonium anomaly. In summary; there are reasons to suspect that metastable charmonium states exist more massive than the ψ', that their production rates in hadronic interactions are comparable to the χ states and that their decays could feed the lower mass signals leading to a significant enhancement over the present theoretical expectations. Three main candidates occur:

(i) conventional charmonium states $2^{-+}, 2^{--}$, predicted at 3.81 to 3.85GeV [2,3] and thereby metastable (parity forbids the $D\bar{D}$ decay),

(ii) the radial excitation $2^3P_1(\approx 3.9GeV)$ whose decay $\rightarrow DD^*$ is near threshold where radial wavefunctions can suppress widths[4,5,6] and its partner $2^3P_2(3.9-4.0GeV)$ whose decays into $D\bar{D}, D\bar{D}^*$ are similarly suppressed by D-wave phase space and dynamical effects,

(iii)hybrid charmonium states where the gluonic degrees of freedom are dynamically excited in the presence of charmed quarks [7]-[12]. Some of these states are predicted to be metastable if their mass is below DD^{**} threshold ($\approx 4.3GeV$)[9,13,14]; recent works [9,10,11,12] have reinforced the predictions[7,8,12] that this mass region is the most likely for the manifestation of hybrid charmonium states.

These three scenarios have competing claims. The first is conservative and almost certain to be present at some level: the problem is that the decays into the ψ and χ charmonia are suppressed by phase space and/or wavefunction orthogonality (however,the radiative decay of $2^{-+} \rightarrow \psi(3685)+\gamma$ may become detectable if the $\psi(3685)$ contains significant ${}^3D_1$ or other non trivial components in its wavefunction). The radiative transitions $2^3P_{1,2} \rightarrow 2^3S_1+\gamma$ could be significant sources of $\psi(3685)$ if the hadronic width of either 2^3P_2 or 2^3P_1 is suppressed, as suggested in some models [5,6,15].The hybrid excitation on the other hand, is more radical and in consequence more interesting. If such states exist in Nature, then production by hard gluons in a hadronic environment favouring heavy flavours, such as at the Tevatron, may be rather natural. The pathways to feed ψ and χ charmonium states are plentiful and some enhancement of ψ states may be expected. In any event, the definitive test of all of these scenarios is to form invariant mass distributions of ψ χ and ψ' states in combination with $\gamma, n\pi, \eta$ in order to isolate any source(s) more massive than $\psi(3685)$.

Our initial point of departure will be the recent series of papers [16,17,18,19] on the production and decay of heavy quarkonia which have, *inter alia*, stressed the important role that colour-octet components can play, especially in the case of P-wave (and, we conjecture, D-wave) quarkonia. The essential physical ideas are as follows.

Any meson is a superposition of many components

$$M = \psi_{Q\bar{Q}} + O(\vec{v})\psi_{Q\bar{Q}g} + \dots \tag{1}$$

in some of which ($e.g. \psi_{Q\bar{Q}g}$) the heavy quark and antiquark are in a colour-octet state. The probability of the $Q\bar{Q}g$ state is of order $\vec{v}^2$ (heavy quarks don't easily radiate a gluon;$\vec{v}^2 \approx \frac{1}{4}$ for charmonium) and so such components can be neglected for many applications. However, as first pointed out in ref [17], these components play an enhanced role in the decay and production of P states where the $Q\bar{Q}g$ contribution to the quarkonium annihilation competes with, and in some cases even dominates, that coming from the $Q\bar{Q}$. The essential physics is that the $Q\bar{Q}$ contribution to annihilations of P-wave quarkonium is suppressed by v^2 owing to the angular-momentum barrier which pushes the quarks apart; in the $Q\bar{Q}g$ component the $Q\bar{Q}$ are in S-wave for which there is no angular momentum suppression though the probability to find this component in the wavefunction is only at $O(v^2)$ and hence the $Q\bar{Q}$ and $Q\bar{Q}g$ contributions are comparable in production or decays.

These ideas have been extended and applied to charmonium production in B-decays [16] and to the production of both S-wave and P-wave charmonia by gluon fragmentation[18]. As a result of the colour-octet mechanism, the production of χ states is predicted to play a prominent role, in particular their subsequent decay $\chi \to \psi + \gamma$ is predicted to dominate over direct production of ψ. There is evidence to support this latter prediction and rather general support for the prediction that a major component of heavy quarkonia production at high $p_T \geq 6GeV$ is fragmentation (namely the production of high P_T parton, in particular a gluon, followed by splitting into a quarkonium state)[20,21,22,23].

Even though this important colour octet contribution helps to explain in part the large J/ψ production recently observed at the Tevatron, it still appears to fall short of explaining the full strength of ψ production, both there [20,21,22] and also in B-decay [16]. The prediction[16] in the latter case is that $BR(B \to \psi + \ldots) = 0.23\%$ to be compared with $(0.74 \pm 0.21)\%$ (where the cascade from χ states has been accounted for and we have used the new PDG values [24])

Production of one or more additional metastable charmonium state(s) with masses greater than 3685MeV and with significant branching ratios into the conventional charmonia could be responsible for the enhanced signals in the above set of experiments.

2 Colour Octet States

Independent of the above, there has been considerable interest in the possible existence of hybrid states [7,8,9] where the gluonic degrees of freedom are excited in the presence of the quarks. Early extensive studies [8] modelled these states as $Q\bar{Q}g$ where the quarks were in an overall colour octet state; subsequent developments have included lattice simulations [10] and modelling in terms of flux tubes connecting the quarks [9]. In these latter the conventional mesons arise when the flux tube is in its ground state and new hybrid states arise when the flux tube is excited. In the case of an unexcited flux tube, the colour can be factored onto the $Q\bar{Q}$ such that they are colour singlet; when the colour flux tube is excited such a factorisation is non trivial and overlap with the colour octet simulations of refs [7,8] may arise but a detailed relationship is still unclear.

In contrast to the conventional quarkonium (eq 1), the hybrid states may be considered as [8,19]

$$H = \psi_{Q\bar{Q}g} + O(\vec{v})\psi_{Q\bar{Q}} + \ldots \tag{2}$$

If for the ground state the $(Q\bar{Q})_8$ are in S-wave [8], the production of the hybrid state can be dominated by the colour octet mechanisms of refs [16,17,18] in *leading order*.

The overall quantum numbers of the hybrids depend on whether the gluon coupling is chromo-electric or magnetic[8], forming respectively positive and negative parity families, $(0,1,2)^{++}, 1^{+-}$ or $(0,1,2)^{-+}, 1^{--}$. In particular, among the chromomagnetic configurations we note the state with $J^{PC} = 2^{-+}$ which would be $D-$wave in colour singlet quarkonium, and hence highly suppressed in short distance production ($O(v^4)$), but produced in leading order in the octet configuration,

$$D(g \to Q\bar{Q}2^{-+}) \approx R''_d(0)^2 \approx v^4 \times R_s(0)^2 \tag{3}$$

$$D(g \to Q\bar{Q}gJ^{-+}) \approx (2J+1)R^2_{8,s} \tag{4}$$

where $R^2_{8,s}$ is the non-perturbative probability for $Q\bar{Q}$ in the S-wave colour octet configuration to fragment into a colour singlet bound state and is expected, following ref [16,17,18], to be proportional to the probability of finding the $Q\bar{Q}g$ octet component in the hadron wavefunction. Thus if the $Q\bar{Q}g$ "octet modelling" of hybrids[7,8,19] is a guide, we would expect that any 2^{-+} charmonium production at the Tevatron will favour the hybrid configuration.

In the case of chromoelectric gluon couplings, which lead to the same overall quantum numbers as those of P-wave charmonium,ref [18] finds for the gluon fragmentation probabilities

$$P_{g\to\chi_J} \approx (2J+1)\frac{\pi\alpha_s H_8}{24m_Q} - R_J\frac{\alpha_s^2 H_1}{108m_Q} \tag{5}$$

where $R_{0,1,2} = 5, 4, 16$ respectively and $H_1 \approx 15MeV$, $H_8 \approx 3MeV$. If $\alpha_s \approx \frac{1}{4}$, this implies fragmentation probabilities of $(0.4, 1.8, 2.4)10^{-4}$ for $\chi_{0,1,2}$ where in each case the octet piece dominates. Multiplying the fragmentation probabilities by the appropriate radiative branching ratios for $\chi_J \to \psi + \gamma$ of $(0.7, 27, 14)10^{-2}$ yields the probability of J/ψ in a gluon jet of approximately 8×10^{-5}, over an order of magnitude larger than the probability 3×10^{-6} for direct fragmentation of a gluon into J/ψ[18].

Insofar as the empirical value $H_8 \approx 3MeV$ subsumes the octet probability $O(v^2 \approx \frac{1}{4})$, we may estimate the probabilities for fragmentation into the hybrid counterparts by rescaling the H_1, H_8 accordingly

$$H_8^{hybrid} \approx 12MeV \tag{6}$$

$$H_1^{hybrid} \approx 3.75MeV \tag{7}$$

in which case the fragmentation probabilities for the hybrids are

$$P_{g\to\chi_g}(0^{++}, 1^{++}, 2^{++}) = (2, 8, 13) \times 10^{-4} \tag{8}$$

These give a total probability $O(10^{-3})$ which would lead to the required enhancement of the J/ψ signal if $B.R.(\psi + \ldots) \approx 4 \times 10^{-2}$.

A problem is that models put these *positive* parity hybrid states significantly above the charmed hadron pair threshold with consequent strong decay widths $O(100)MeV$. Therefore we find do not anticipate a large $(O(10^{-2}))$ branching ratio into charmonium unless there is strong mixing with the nearby radial charmonium states in particular $2^3P_{1,2}(3.9 - 4.0GeV)$ (see section 3)

By contrast *negative parity* hybrids could be a copious source of the ψ states due to two fortunate circumstances common in models. First, models based on constituent gluons[7,8], flux tubes[9,11], quenched heavy quark lattice QCD[10] and QCD sum rules[25] all anticipate negative parity hybrid charmonium states, including $(0,1,2)^{-+}, 1^{--}$, typically in the range $4.2 \pm 0.2 GeV$. In addition the negative parity decays into $D\bar{D}, D^*\bar{D}$ are suppressed in both constituent gluon models[13,14] and in flux tube models[9] such that the effective strong decay threshold is at $DD^{**} \approx 4.2 - 4.3 GeV$ (an estimate of their widths leads typically to $O(1 MeV)$[6]). Thus they offer *a priori* the possibility of radiative branching ratios into χ, ψ of $O(10^{-3})$ or via hadronic modes at the 10^{-2} level if the gluonic tumbledown transitions $\psi(2S) \to \psi(1S) \geq 50\%$ and predictions of similar rates for $1D$-states[26] are any guide.

Production of these states in $\gamma\gamma$ processes has been discussed in[19] but I know of no detailed calculations analogous to[18] of gluonic fragmentation, factoring out chromomagnetic and electric gluon modes. Ref[19] found that in $\gamma\gamma$ decays the colour singlet and octet components compete (for the hybrid decay) and cancel in perturbation theory; in the hadronic decays this cancellation does not occur and the colour octet component is dominant. Optimistically one could take over the results of equation(8) to the negative parity case in which case one finds a significant possibility of ψ production competing with the existing signal (or for the $\psi(3685)$ a dominant effect). However, we suspect that a more realistic calculation will find that the results for the negative parity states will effectively be reduced by $O(v^2)$ in probability relative to those for the analogous positive parity states, (the $g^*g \to Q\bar{Q}g$ transition with magnetic $J^P = 1^+$, involves an effective $P-$wave $(^3P_1)$ coupling relative to the $^3S_1$ picture and so we will form our more conservative estimate by reducing the octet contribution in equation(5) by $O(v^2) \approx \frac{1}{4}$).

The singlet contribution in equation(5) also needs to be reconsidered. For the 0^{-+} hybrid, the colour singlet component is $^1S_0$ and so the effective contribution

$$H_1(0^{-+}) \approx \frac{3}{2\pi}\frac{R_s(0)^2}{m_Q^4} \times 0(v^2) \approx 27 MeV \tag{9}$$

For the case of the exotic 1^{-+} and the 2^{-+} we need only include the octet piece in our estimates (see eq(15) *et seq* below). So these lead to our "optimistic" and "conservative" $(0(v^2)$ suppression) estimates for the production probabilities for the negative parity hybrids in the $Q\bar{Q}g$ picture

$$3 \times 10^{-4} \leq P(2^{-+}) \leq 13 \times 10^{-4} \tag{10}$$

$$2 \times 10^{-4} \leq P(1^{-+}) \leq 4 \times 10^{-4} \tag{11}$$

$$10^{-5} \leq P(0^{-+}) \leq 1 \times 10^{-4} \tag{12}$$

While these follow rather naturally in the $Q\bar{Q}g$ picture they are probably only an order of magnitude guide for the flux tube model of hybrids. More detailed study is warranted in the latter case as the current estimates are encouraging: in both models the hadronic widths are of order $1MeV$[6] due to the effective threshold being that of DD^{**}, and so the feeding of $\psi(3685), \psi$ with significant branching ratios leading to an effective probability $0(10^{-5} - 10^{-4})$ may be possible when all states and decay chains are summed. The upper end of this range would correspond to this being the dominant contribution to ψ production at the Tevatron.

3 Narrow Charmonium

In potential models of charmonium, additional narrow states are expected above the $\psi(3685)$. Most probable are $2^{-+}, 2^{--}$ predicted at 3.81 to 3.82GeV[2,3] and the possibility that $2^3P_{1,2}(3.9-4.0GeV)$ have suppressed hadronic widths due to quantum numbers or nodes in form factors manifested in decays near threshold [4].We consider these in turn.

An estimate of the production rate for the 2^{-+} follows by assuming this to be dominated by the $Q\bar{Q}g$ component of the wavefunction. In this case we take the result in eq(10) and weigh it by $O(v^2) \approx \frac{1}{4}$, leading to probability

$$10^{-4} \leq P(2^{-+}) \leq 3 \times 10^{-4}. \tag{13}$$

We expect that production of the 2^{--} will be much reduced as there is no obvious octet enhancement available, and we shall not consider this state further here.

The total hadronic width of 2^{-+} is expected to be in the range $50keV - 800keV$. Our argument is as follows.

By analogy with ref[17] we separate the decay into singlet and octet pieces

$$\Gamma(^1D_2) = H_1^d \times \frac{4\pi\alpha_s^2}{3} + H_8 \times \frac{\pi n_f \alpha_s^2}{3} \tag{14}$$

where[27]

$$H_1^d = \frac{R_d''(0)^2}{2\pi m_Q^6} \approx 200keV \tag{15}$$

leading to a width estimate, in the absence of colour octet contribution, of $O(50keV)$. For the octet contribution, H_8, we take two values: one is the same as used for the 2^{++} (eq 5; $H_8 = 3.3 \pm 0.7MeV$) and the other will be to reduce this by $O(v^2) \approx \frac{1}{4}$ for the reasons outlined prior to eq(9). Thus for the octet component alone the width would range between $120keV \leq \Gamma_8 \leq 750keV$. Note that the small (large) widths correlate with small (large) production probabilities; hence the ratio of these quantities is less uncertain (and is the relevant quantity that will enter in our estimate of the ψ yield).

Combining the singlet and octet contributions leads to a width estimate

$$170keV \leq \Gamma(2^{-+}) \leq 800keV \tag{16}$$

(note that this also suggests a hybrid 2^{-+} annihilation width of $O(1MeV)$)

To estimate the branching ratios into $\psi(3685), \psi$ and cascades via ${}^1D_2 \rightarrow \gamma +{}^1 P_1;{}^1 P_1 \rightarrow \psi + \ldots$ we use refs[27,28], rescaled for a ${}^1D_2 \approx 3.81GeV$.

The ${}^1D_2 \rightarrow \psi(3685) + \gamma$ is suppressed by wavefunction orthogonality unless there is ${}^3D_1$ presence in the $\psi(3685)$. The rate is

$$\Gamma({}^1D_2 \rightarrow \psi(3685) + \gamma) = O(2keV) \times p_d \tag{17}$$

where p_d is the D-wave probability. This implies a branching ratio below 1%. This could double the $\psi(3685)$ strength but does not seem helpful for explaining a 30-fold enhancement unless the intrinsic production rate of the ${}^1D_2$ is larger than our estimates.

Although this is unlikely to resolve the $\psi(3685)$ anomaly it does offer the hope of isolating some "missing" charmonium states in the Tevatron and $B \rightarrow \psi + \ldots$ data. In this regard,the cascades to $\psi(3095)$ may be interesting. Ref[27] predicts

$$\Gamma({}^1D_2 \rightarrow{}^1 P_1 + \gamma) = 12keV(\frac{k}{100MeV})^3 \tag{18}$$

where k is the photon momentum. The resulting branching ratio could be 50%. According to ref[28] $B.R.({}^1P_1 \rightarrow \psi + \ldots) \approx 1\%$ and so

$$B.R.({}^1D_2 \rightarrow \psi + \ldots) \approx (4 \pm 3)10^{-3} \tag{19}$$

These estimates suggest that forming mass plots of $\psi + \pi, 2\pi, \gamma, \eta$ etc. may isolate ${}^1P_1$ and ${}^1D_2$ states, and that these will make some additional contribution to the ψ signal at the Tevatron but are unlikely alone to explain the full anomaly.

The final candidate is the production and decay of radial charmonium, in particular $2^3P_{1,2} \rightarrow 2^3S_1 + \gamma$. The 2^3P_2 is predicted to lie 200-300MeV above $D\bar{D}$ threshold but can have a reduced width due to the D-wave phase space and also dynamical effects associated with radial excitations[4,5,15]. The $^3P_1 \to DD^*$ also is near threshold and the S and D-waves are affected by radial wavefunction nodes which can conspire to reduce the width and, in consequence, increase the branching ratios $2^3P_{1,2} \to 2^3S_1 + \gamma$.

The production probabilities of 2^3P_J are estimated as for their 1^3P_J counterparts (eq5 *et seq*). The magnitude of H_1 for the radial is similar to the $1P$ states[2]; the magnitude of the octet contribution is less certain. If it is reduced by radial effects in proportion to the well known colour singlet S-state wavefunctions there is a partial cancellation with the H_1 contribution and hence an overall reduction relative to the $1P$ of two($^3P_1$) to three($^3P_2$). This would imply a probability of 10^{-4} for each of these states in gluon jets, which is still a factor of 100 greater than the *direct* fragmentation into $\psi(3685)$. An order of magnitude increase in the $\psi(3685)$ signal relative to theory would therefore follow if the $BR(2^3P_{1,2} \to 2^3S_1 + \gamma) \approx 10\%$. (A similar conclusion has been made in ref[29])

We can estimate the absolute values of the radiative widths by rescaling the known values[24] for the bottomonium system. Allowing a factor of two uncertainty for wavefunction differences between $c\bar{c}, b\bar{b}$[2] we anticipate $\Gamma(2^3P_{2c} \to 2^3S_{1c}\gamma) \approx 80 - 160keV$ and a similar magnitude for the 2^3P_1 case. Thus these states are likely to be serious candidates for the $\psi(3685)$ enhancement only if their total widths are $\approx 1 - 2MeV$.

In flux tube[5] or $^3P_0$ models[4] the decays of radially excited states can be artificially suppressed if the momenta of the produced DD, DD^* coincide with nodes in the form factors. The D-wave decay of $^3P_2$ and the S, D-wave decays of $^3P_1 \to DD^*$ have widths that are rather sensitive to the parameters and masses. If we choose parameters by fitting the hadronic decays of $\psi(3772)$, $^3D_1$ and other candidate excited ψ states[15] the resulting D-wave contributions for the ^3P_J decays are in the range $2 - 5MeV$. The S-wave contributions are highly sensitive to the positions of the wavefunction nodes and hence, in particular, the masses of the states. If the mass is taken from ref[2], $^3P_1 = 3.95GeV$ then $\Gamma_S \approx 2.5MeV$; if the mass is slightly higher (3.96GeV) the S-wave hits a node and the width is killed.

Thus model calculations of the hadronic widths suggest that $^3P_2$ has width $\approx 2 - 5MeV$, and that the $^3P_1$ width may be similar though this latter result is highly sensitive to the choice of parameters.

Our conclusion is that $^1D_2, ^3D_2$ charmonium states may be present in the CDF data and detectable but are unlikely to explain the $\psi(3685)$ enhancement. The radially excited states $2^3P_{1,2}$ may have suppressed widths enabling them to make a measurable contribution, though unlikely on their own to explain the full signal.If the colour octet production mechanism is important, as refs[16,17,18] have argued, and if hybrid states containing dominant gluonic excitations exist, then these states are likely to make a significant contribution to the ψ and ψ' signals at the Tevatron, and may also be present in the $B \to \psi + \ldots$. While our estimates are at this stage only approximate, they do suggest that these various states may be present at the right order of magnitude to warrant a serious study. Our results suggest that a significant percentage of ψ, ψ' production at the Tevatron, in B-decay, or in gluon jets at LEP and HERA, could come from higher mass metastable charmonium and that invariant mass plots including the $\psi, \psi(3685)$ may reveal new charmonium states.

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