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RECENT DEVELOPMENTS IN CHARM SPECTROSCOPY: $\mathbf{X}(3872)$, $\mathbf{D}^*_{s\mathrm{J}}(2317)^+$ and $\mathbf{D}_{s\mathrm{J}}(2463)^+$

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ABSTRACT

The past year has seen reports of evidence for several remarkable hadronic states. Three of these new states, the X(3872), $\mathrm{D}^*_{s\mathrm{J}}(2317)^+$ and $\mathrm{D}_{s\mathrm{J}}(2463)^+$, are mesons containing (as a minimum) charm quarks and strange or charm antiquarks. In this contribution I will concentrate on the X(3872) due to limitations of space, and will review what is known experimentally, what theorists have suggested regarding the interpretation of this state, and how future experimental studies might distinguish between the various theoretical assignments. The $\mathrm{D}^*_{s\mathrm{J}}(2317)^+$ and $\mathrm{D}_{s\mathrm{J}}(2463)^+$ will also be briefly discussed.

1 Introduction: Heavy Quarkonium Spectroscopy

To set the stage for our discussion of the new mesons, it is useful to recall our previous, apparently numerically accurate understanding of the spectrum of heavy quarkonium, as it was known before 2003. (We will specialize to charmonium for this discussion.) Since the charm quark is moderately heavy, it is widely believed that a quark potential model provides a reasonable approximation to the charmonium system. In its simplest form this potential model picture assumes the nonrelativistic Schrödinger equation, with a color Coulomb potential at small $c\bar{c}$ separations from OGE (one gluon exchange) and a linear confining potential at large distances,

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br \ . \tag{1}$$

This zeroth-order spin-independent potential is then augmented by the inclusion of spin-dependent forces. These are usually taken to be the Breit-Fermi Hamiltonian from OGE (which includes spin-spin, spin-orbit and tensor terms) and the inverted spin-orbit of linear scalar confinement. For the equal-mass $c\bar{c}$ case this spin-dependent Hamiltonian is

$$\mathrm{H_I} = \frac{32\pi\alpha_s}{9m_c^2}\,\delta(\vec{r})\,\vec{\mathrm{S}}_c\cdot\vec{\mathrm{S}}_{\bar{c}} + \frac{2\alpha_s}{m_c^2 r^3}\,\vec{\mathrm{L}}\cdot\vec{\mathrm{S}} + \frac{4\alpha_s}{m_c^2 r^3}\,\mathrm{T} - \frac{b}{2m_c^2 r}\,\vec{\mathrm{L}}\cdot\vec{\mathrm{S}}\ . \tag{2}$$

The strong effect of the spin-spin term on the wavefunctions of S-wave states at short distances is often treated by incorporating the spin-spin term in the "zeroth-order" potential $V(r)$. This contact interaction must then be replaced by a nonsingular distribution, which is typically a relatively narrow Gaussian with a width of $1/\sigma$. We follow this approach, which gives a potential model of charmonium with the four parameters α_s, b, m_c and σ. Fitting this model to the masses of the 11 established charmonium states in the 2004 PDG [1] (with equal weights) gives the spectrum shown in fig.1 and the parameter values $\alpha_s = 0.5461$, $b = 0.1425$ GeV^2, $m_c = 1.4794$ GeV and $\sigma = 1.0946$ GeV. This fit is described in detail elsewhere, [2] and gives a very reasonable rms error of 13.6 MeV. The well known potential models of Godfrey and Isgur [3] and (for charmonium specifically) Eichten *et al.* [4] assume very similar physics, but replace the nonrelativistic kinetic energy in the Schrödinger equation by a relativized form.

Recent developments in lattice gauge theory have led to reasonably well constrained mass predictions for the spectrum of heavy quarkonium states (*albeit* usually in the quenched approximation). As an example, in fig.2 we show the results of Liao and Manke, [5] which are similar both to experiment and to the potential model. (Actually, since this potential model and quenched

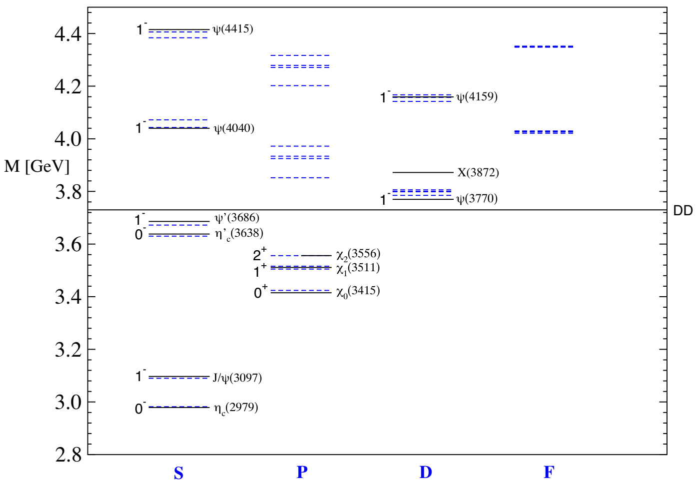

Figure 1: *The spectrum of charmonium states predicted by the $c\bar{c}$ potential model described in the text (dashed), fitted to the 11 well-established experimental states [1] (solid). The X(3872) is also shown, although its identification with*

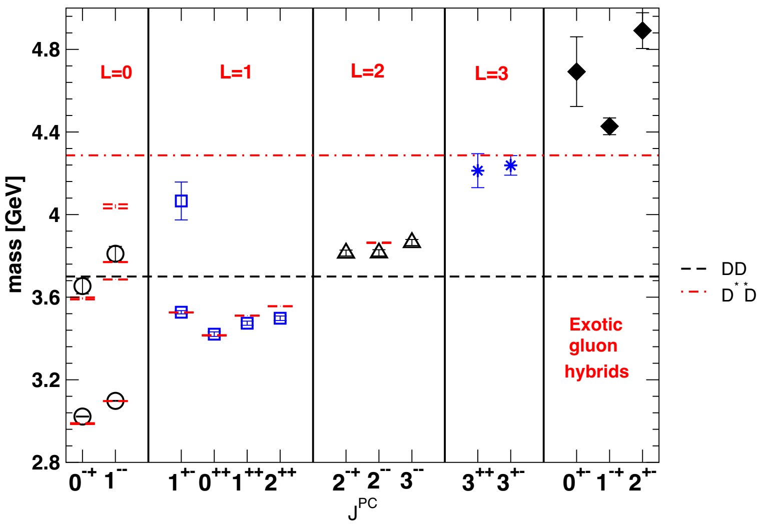

Figure 2: *The spectrum of low-lying charmonium states predicted by lattice gauge theory in the quenched approximation.* [5] *Compare with fig.1.*

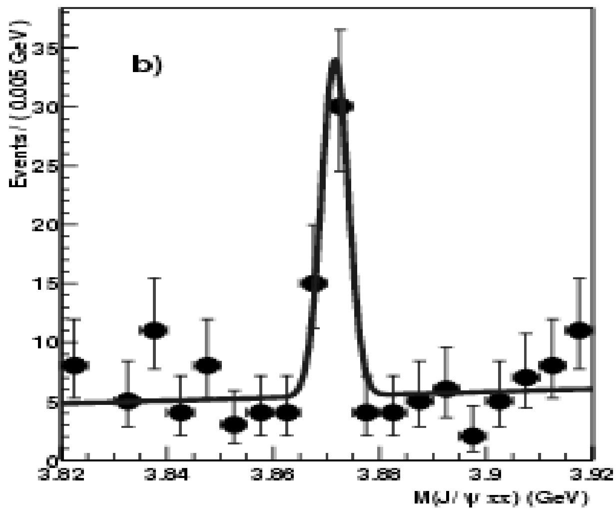

Figure 3: *The X(3872), first reported by the Belle Collaboration in* $J/\psi\,\pi^+\pi^-$. [6]

LGT both neglect decay loops, both approaches may share similar systematic errors.) There are some indications that the higher-L charmonium states are predicted to lie at higher masses by LGT. Small higher-L multiplet splittings are evident in both approaches. The most interesting LGT prediction may be the mass of the J^{PC}-exotic 1^{-+} charmonium hybrid, which is expected at about 4.4 GeV. (We note in passing that the experimental 1^{+-} h_c state shown near 3.52 GeV in the LGT figure has been withdrawn.)

2 The X(3872)

The recent discoveries of the X(3872), $D^*_{sJ}(2317)^+$ and $D_{sJ}(2463)^+$ have challenged our understanding of heavy quark meson spectroscopy, since these states are in serious disagreement with theoretical expectations. The X(3872) was originally discovered by the Belle Collaboration [6] in B meson decay ($B^{+-} \to K^{+-}\pi^+\pi^- J/\psi$) as a narrow peak in the $J/\psi\pi^+\pi^-$ invariant mass distribution. The state had a very high statistical significance in the Belle data (in excess of 10σ), and has since been confirmed by CDF II, [7] D0 [8] and BABAR. [9]

This decay mode suggested that the state might be one of the two missing narrow charmonium states in the L = 2 $c\bar{c}$ multiplet, which have $J^{PC} = 2^{-+}$ or 2^{--}. These two $c\bar{c}$ states are special in that they do not have open-flavor decay modes, unlike the other $c\bar{c}$ states above DD threshold, and consequently are expected to have rather small total widths. (A total width of ca. 1 MeV is expected from annihilation and radiative decays.) Subsequent theoretical study has added the $J^{PC} = 3^{-+}$ $^3D_3$ $c\bar{c}$ state to the list of X(3872) candidates; it can decay to DD, but the centrifugal barrier implies that this will nonetheless be a relatively narrow state. [10, 11] Alternatively, the X(3872) might be a more complicated state such as a charm meson molecule, which contains a $c\bar{c}$ pair that is combined with other (light) constituents.

The near equality of the reported mass of the X(3872) and the neutral D^0D^{*0} threshold of 3871.5 ± 0.5 MeV immediately suggested that the X(3872) could be a D^0D^{*0} system (a bar is implicit here, such as $D^0\bar{D}^{*0}$ or $\bar{D}^0D^{*0}$ or a linear combination), either a weakly bound "molecule" [12, 13, 14, 15, 16, 17] or perhaps simply a cusp phenomenon due to the opening of a new channel. [18] Note that the mass of a charged ($D^{\pm}D^{*\mp}$) pair is rather higher, 3879.5 ± 0.7 MeV, so the X(3872) would presumably be a pair of neutral charmed mesons.

Table 1: *Experiments reporting the X(3872).*

Collab.	Mass (MeV)	Width (MeV)	mode
Belle [6]	$3872.0 \pm 0.6 \pm 0.5$	< 2.3, 95% *c.l.*	$J/\psi\,\pi^+\pi^-$
CDF II [7]	$3871.3 \pm 0.7 \pm 0.4$		"
D0 [8]	$3871.8 \pm 3.1 \pm 3.0$		"
BABAR [9]	3873.4 ± 1.4		"

Since this implies a very weakly bound system, with a binding energy of at most about 1 MeV (from the experimental mass uncertainties), the dominant binding mechanism would presumably be the longest-ranged strong interaction, one pion exchange. Fortunately we know the strength of the $D^*D\pi$ coupling experimentally from D^* decay, so this effect can be estimated with only moderate uncertainty. One pion exchange does indeed provide an attraction in this system, and the forces are very close to the strength required to bind a D^0D^{*0} pair in S-wave. [12, 16] With the addition of (also attractive) short-ranged quark-gluon forces, it does appear that a weakly bound D^0D^{*0} molecule is expected theoretically. [16]

The naive expectation for strong decays of a weakly bound meson molecule is that it should decay as its constituents do. In this case only the D^* decay modes are relevant, so we would expect decays of a D^0D^{*0} bound state to populate the final states $D^0D^0\pi^0$ and $D^0D^0\gamma$. However the D^{*0} has a rather small total width (not yet measured but probably only about 50 keV), so another decay mechanism, internal rescattering, is expected to dominate decays. The D^0D^{*0} pair can internally rescatter by constituent interchange into charmonium and a light meson, for example $J/\psi\,\rho^0$ and $J/\psi\,\omega$. Evaluation of these rescattering amplitudes by Swanson [16] leads to the prediction that they should be the dominant decay modes of a D^0D^{*0} molecule, (see Table 2) and that as a result $J/\psi\pi^+\pi^-$ and $J/\psi\pi^+\pi^-\pi^0$ should be the dominant final states populated by X(3872) decays. The remarkable prediction of comparable branching fractions to modes with different isospins ($J/\psi\pi^+\pi^-\pi^0$ and $J/\psi\pi^+\pi^-$ here are $I = 0$ and $I = 1$ respectively) is a simple consequence of the maximal isospin mixing implied by a D^0D^{*0} bound state. Additional predictions of branching fractions that follow from the DD^* molecule model have been given recently by Swanson. [17]

Table 2: *The dominant decay modes of an S-wave* 1^{++} D^0D^{*0} *molecule* [16] *for* $\mathrm{E_B} = 1$ *MeV.*

mode	$D^0\bar D^0\pi^0$	$D^0\bar D^0\gamma$	$\pi^+\pi^-J/\psi$	$\pi^+\pi^-\pi^0J/\psi$	$\pi^0\gamma J/\psi$
Γ^{thy}(keV)	66	36	1215	820	80

The prediction of comparable branching fractions to $J/\psi\,\pi^+\pi^-$ and J/ψ $\pi^+\pi^-\pi^0$, through the intermediate states $J/\psi\,\rho^0$ and $J/\psi\,\omega$ respectively, is a remarkable prediction of the D^0D^{*0} molecule model when combined with the assumption of an internal rescattering mechanism. A simpler question regarding $J/\psi\,\pi\pi$ modes is whether there is a $J/\psi\,\pi^0\pi^0$ signal present with a comparable strength to $J/\psi\pi^+\pi^-$. [19] The presence of this $J/\psi\,\pi^0\pi^0$ mode would imply C=(−) quantum numbers, whereas the usual molecule assumption is that this is a C=(+) state. ($J^{PC} = 1^{++}$). The mass distribution of the $\pi\pi$ system in $J/\psi\pi^+\pi^-$ is also an interesting question, since there is evidence that it does peak at higher mass, but it is not yet clear whether the mass and width of the distribution are consistent with a ρ^0 source. Similarly, in the molecule model the $\pi^+\pi^-\pi^0$ system in X(3872) $\to J/\psi\pi^+\pi^-\pi^0$ decays should be strongly peaked at high invariant mass, if the $\pi^+\pi^-\pi^0$ source is an ω meson.

Although the near equality of the X(3872) mass and the D^0D^{*0} threshold makes the molecule a very compelling picture (this is currently the favored assignment), the $c\bar c$ option is also straightforward to test. The $J^{PC} = 2^{-+}$ and 2^{--} $^1D_2$ (h_{c2}) and $^3D_2$ (ψ_2) $c\bar c$ assignments lead to predictions of relatively large radiative transitions to 1P charmonium states, for which Barnes and Godfrey [10] found

$$\Gamma_{h_{c2}\to\gamma\chi_2} = 0.09 \text{ MeV} \tag{3}$$

and

$$\Gamma_{h_{c2}\to\gamma\chi_1} = 0.36 \text{ MeV} \tag{4}$$

for an initial $^1D_2$ $h_{c2}(3872)$, and

$$\Gamma_{\psi_2\to\gamma h_c} = 0.46 \text{ MeV} \tag{5}$$

for a $^3D_2$ $\psi_2(3872)$. (See also Eichten, Lane and Quigg [20] for radiative transition rates.) Since the total width of the X(3872) is below 2.3 MeV (95%

c.l.), a $c\bar{c}$ assignment would evidently imply large branching fractions of at least $\approx 20\%$ to radiative modes. These can be searched for through the large secondary radiative transitions of the P-wave mesons to S-wave charmonia, $h_{c2} \to \gamma\chi_J \to \gamma\gamma J/\psi$ and $\psi_2 \to \gamma h_c \to \gamma\gamma\eta_c$ respectively.

At present we only have an experimental limit for one of these radiative transitions. In their original paper Belle reported

$$\frac{B_{X(3872)\to\gamma\chi_1}}{B_{X(3872)\to J/\psi\pi^+\pi^-}} < 0.89, \quad 90\% \text{ c.l.} \tag{6}$$

Unfortunately, this is not constraining without an independent estimate of the partial width of the poorly understood dipion mode.

Another approach to testing possible assignments for the X(3872) is to search for other decay modes. For example, a D-wave $c\bar{c}$ X(3872) will not appear in e^+e^-, and a 2^{--} $^3D_2$ (ψ_2) $c\bar{c}$ will not be seen in $\gamma\gamma$ collisions. Neither e^+e^- nor $\gamma\gamma$ would show a 1^{++} DD* molecule (although $\gamma\gamma^*$ would, with sufficient statistics). A 2^{-+} $^1D_2$ (h_{c2}) $c\bar{c}$ in contrast *will* be produced in $\gamma\gamma$, and the great sensitivity of current e^+e^- machines makes this a useful production channel to investigate. Unfortunately, the $\gamma\gamma$ couplings of $c\bar{c}$ states are expected to fall rapidly with increasing L; a hypothetical D-wave $c\bar{c}$ $h_{c2}(3840)$ is predicted to have a $\gamma\gamma$ width of only 20 eV. [21]

There are now very strong recent experimental limits on production of the X(3872) in both e^+e^- and $\gamma\gamma$. Yuan, Mo and Wang [22] used ISR data from BES to give an upper limit of

$$\Gamma_{e^+e^-}(X(3872)) \cdot B_{X(3872)\to J/\psi\pi^+\pi^-} < 10 \text{ eV}, \quad 90\% \text{ c.l.}, \tag{7}$$

and a new analysis of CLEO III data [23] sets limits of

$$\Gamma_{e^+e^-}(X(3872)) \cdot B_{X(3872)\to J/\psi\pi^+\pi^-} < 8.0 \text{ eV}, \quad 90\% \text{ c.l.} \tag{8}$$

and

$$(2J+1)\Gamma_{\gamma\gamma}(X(3872)) \cdot B_{X(3872)\to J/\psi\pi^+\pi^-} < 12.9 \text{ eV}, \quad 90\% \text{ c.l.} \tag{9}$$

The X(3872) is not expected to appear in e^+e^- in either of the usual DD* molecule or $c\bar{c}$ assignments, since neither is 1^{--}. The $^3D_2$ $c\bar{c}$ assignment however does imply a (rather weak) coupling to $\gamma\gamma$ of $\Gamma^{thy}_{e^+e^-}(X(3872)) \approx 20$ eV, [21] so this is a useful experimental limit. Unfortunately the branching fraction of the X(3872) to $J/\psi\pi^+\pi^-$ is unknown at present, however once this is established it may be possible to use this $\gamma\gamma$ width limit to eliminate a dominantly $c\bar{c}$ assignment.

3 $\mathbf{D}^*_{sJ}(2317)^+$ and $\mathbf{D}_{sJ}(2463)^+$

For completeness we will also briefly discuss the new charm-strange mesons $D^*_{sJ}(2317)^+$ and $D_{sJ}(2463)^+$, since some aspects of these states are reminiscent of the X(3872). Unfortunately there is insufficient space in this report for a detailed discussion, so only the basic issues will be noted.

The $D^*_{sJ}(2317)^+$ was the first of the anomalous new charm mesons to be reported. It was discovered by the BABAR Collaboration [24] as a very narrow peak in the final state $D_s^+\pi^0$, at a mass of 2.32 GeV. This discovery was quickly followed by the report of a second narrow state by the CLEO Collaboration, [25] the $D_{sJ}(2463)^+$ in $D_s^{+*}\pi^0$. In both cases the widths of the states were consistent with experimental resolution.

There were quark model states in the $c\bar{s}$ sector that might *a priori* have been identified with these new discoveries, a 0^+ $^3P_0$ scalar and a 1^+ mixed $^1P_1$ and $^3P_1$ axial vector. The reported properties however were far from theoretical expectations; the 0^+ $^3P_0$ $c\bar{s}$ had been predicted by Godfrey and Isgur to have a mass of 2.48 GeV, and the two 1^+ states were expeced near 2.55 GeV. [3] In addition, both missing states were predicted to have very large total widths of 100s of MeV. [29] Identification with the new experimental states would require that the potential model was in error by over 150 MeV, whereas past experience suggested errors of ca. 20 MeV in the $c\bar{s}$ sector. If one could accept this mass discrepancy, the narrow widths could then be understood; at masses of 2.32 GeV and 2.46 GeV the 0^+ and 1^+ $c\bar{s}$ states would be below their lowest open-flavor decay modes (DK and D*K respectively), and would have to decay to strongly suppressed modes such as the isospin-violating $D_s^+\pi^0$ and $D_s^{*+}pi^0$. Alternative explanations for these new states, such as a DK bound state for the $D^*_{sJ}(2317)^+$, were also proposed; it was noted that the very strong coupling predicted for a $c\bar{s}$ quark model state to DK would induce a strong attraction in the DK channel, which might result in the formation of an S-wave bound state. [26]

It may be that the mass errors in the potential model predictions for these states and their predicted large widths are related effects. It is well established that virtual decays of mesons to two-meson continua can give rise to large, negative mass shifts in charmonium. [27, 28] These effects should be very large for the 0^+ and 1^+ $c\bar{s}$ states, which were predicted to have especially large open-flavor decay couplings to DK and D*K respectively. In this case the physical states would paradoxically be narrow because their decay couplings are so large; the resulting mass shifts have pushed the states below their open-flavor decay thresholds.

Whether this remarkable possibility is indeed numerically realistic given our current strong decay models, and what the resulting $c\bar{s} \leftrightarrow$ DK mixing would predict for observables, are two of the most important questions raised by the discovery of the new narrow resonances.

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