GLUONIC EXCITATIONS IN HEAVY MESONS AND THEIR DECAYS BY FLUX-TUBE BREAKING

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ABSTRACT

We have examined decays of low-lying gluonic excitations of mesons (hybrids) by chromoelectric flux-tube breaking. An analytical calculation of non-relativistic flux-tube model decay amplitudes is performed in an harmonic oscillator approximation. Specific decay signatures of all $J^P C$ charmonium hybrids are identified and the widths predicted. We introduce a new selection rule which can be used to understand the systematics of numerical decay calculations.

1. Mesons with an excited gluonic field

We define charmonium hybrids as charm-anticharm bound systems (mesons) with an excitation of the gluonic degree of freedom. Unless otherwise stated, we just refer to these systems as ‘hybrids’ from now on. They represent new confined states of QCD beyond the quark model, and hence an important experimental test of QCD. Interesting features of hybrids are:

• Their uniqueness as a bound systems with both ‘valent’ fermions and bosons.
• Hybrids often have exotic quantum numbers not found in the quark model, e.g. $J^P C = 0^{+-}, 1^{++}$ and $2^{+-}$ for the lowest lying hybrids in the flux-tube model, which facilitate easier experimental detection of non-quark model states.
• Hybrids are expected to have masses of $4.1 \pm 0.4$ GeV (literature average).†
• Some hybrids are believed to be very stable (i.e. having small widths). For hybrids below the $D^{**}D$ threshold the flux tube model predicts very small widths (decays into $DD, D^*D$ and $D^*D^*$ are almost forbidden). Hence we are specifically interested in hybrid decay widths to $D^{**}D$ above threshold.

The reason for our interest in charmonium hybrids derives from the expectation that their masses are better defined than is the case for their light quark counterparts and, due to the smaller amount of phase space available in the corresponding decay channels, their widths are smaller. Bottomonium hybrids are expected to be more difficult to produce than charmonium hybrids. Experimentally, the situation is

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†A mass of $\approx 4.3$ GeV has been estimated with a numerical simulation in the flux-tube model. The fact that these masses are well-defined means that we can make firm experimental predictions.
(i) **Light quark hybrids**: There has recently been a claim of a broad $J^{PC} = 1^{-+}$ exotic resonance with isospin one by the AGS at Brookhaven, with mass in the range 1.6 – 2.2 GeV. They studied pion-nucleus inelastic scattering, and found evidence for the above resonance decaying into $f_1(1285)\pi^- \rightarrow K^+\pi^0\pi^-$, a process which is predicted to be important (with a width of 50 MeV) in the flux tube model. The current data suffers from low statistics, making its discovery an ambiguous claim and its existence in need of independent corroboration.

(ii) **Charmonium hybrids**: Beijing $e^+e^-$ annihilation experiments may soon have high enough luminosity to produce $J^{PC} = 1^{--}$ hybrids above the $DD$ threshold.

(iii) **Bottomonium hybrids**: Detection in $e^+e^-$ annihilation of a $J^{PC} = 1^{--}$ hybrid above the $BB$ threshold at the SLAC B-factory is a possibility.

2. **The flux-tube model decay amplitude for hybrid $\rightarrow D^{**}D$**

In the Isgur-Paton non-relativistic flux-tube model of QCD the gluonic field of a hybrid is represented by *beads*, which are connected to each other and the quarks at the ends via a non-relativistic string. The gluonic field is excited, giving rise to an excited adiabatic potential between the quarks, which enables the study of hybrids without further experimental input.

The decay amplitude of $A \rightarrow BC$ by pair creation is similar to the $^3P_0$-model amplitude (where $A$ is the initial meson decaying into mesons $B$ and $C$). There is an additional overlap of the string of $A$ to break at the pair creation position into the strings of $B$ and $C$, though. The model also predicts an overlap for hybrid $\rightarrow BC$. This prohibits pair creation on the hybrid $q\bar{q}$-axis.

We perform an *analytical calculation* of the decay amplitude hybrid $\rightarrow D^{**}D$ by assuming the outgoing $D^{**}$ and $D$ wave functions to be $L=1$ and $L=0$ S.H.O. wave functions with inverse radii $\beta_{D^{**}}$ and $\beta_D$ respectively. The initial hybrid wave function is proportional to $r^\delta D(\Omega) \exp(-\beta_{hybrid}^2 r^2/2)$, where $D(\Omega)$ is a Wigner rotation function and $0 < \delta < 1$.

The calculation is performed for the case $\beta_{D^{**}} = \beta_D = \beta$. The main reason for this simplification is that (a) the $D^{**}$, $D^*$ and $D$ are expected to have similar $\beta$’s, and that (b) the systematics of earlier numerical calculations for light quarks can be understood in this limit.

The only free parameter in the model is the *lattice size* (or longitudinal distance between beads), which is related to the overall normalization of decays. All other parameters have previously been estimated in the context of the model.

For decays of *ordinary mesons into ordinary mesons*, it is generally the case that the $^3P_0$ and the flux-tube models coincide in the limit where the string tension vanishes. It is possible to make a stronger statement: *The $^3P_0$ and flux-tube models coincide when $\beta_B = \beta_C$ even if the string tension is non-zero.* This result at least holds for two final state $L=0$ mesons and for final state $L=0$ and $L=1$ mesons. This also explains the systematics of earlier numerical calculations.

For decays of *hybrid mesons into ordinary mesons*, the flux-tube model predictions are much more distinctive. When $\beta_B = \beta_C$ the hybrid decay width to two $L=0$ mesons
is zero (i.e. hybrid $\rightarrow DD, D^*D$, and $D^*D^*$ is forbidden). Hence the first non-zero decay width is to $L=1$ and $L=0$ mesons. This explains our interest in hybrid $\rightarrow D^{*2}$.

When $\beta_B = \beta_C$ there is also an important selection rule operating in the moving frame of the initial qq-pair for hybrid $\rightarrow D^{*2}$: The one unit of angular momentum of the hybrid around the qq-axis is exactly absorbed by the component of the outgoing $D^*$ angular momentum along the qq-axis.

The dominant decay modes of hybrid $\rightarrow D^{*2}$ are displayed in Table 1. The eight lowest lying hybrids in the model are assumed to have masses of 4.30 GeV or 4.35 GeV (and in addition a small hyperfine splitting, which affects phase space appreciably). They lie around the $D^{*2}$ threshold of $\approx 4.3$ GeV. The magnitudes of the decays are normalized to ordinary meson decays. All resonances are approximated to be narrow. We assume the $D$, $D^{*1+}$, $D^{*1L}$ (low mass), $D^{*0+}$ and $D^{*1H}$ (high mass) have masses 1.87, 2.46, 2.42, 2.40 and 2.45 GeV, respectively. Also $\beta_{\text{hybrid}} = 0.35$ GeV, $\beta = 0.37$ GeV, $\delta = 0.62$ and the $D^{*1L}/D^{*1H}$ mixing is 41$^o$.

Table 1. Dominant widths in MeV for hybrid $(c\bar{c}g) \rightarrow D^{*2}$ for various $J^P C$ in partial wave $L$, both for 4.30 GeV hybrids ($\Gamma_1$) and 4.35 GeV hybrids ($\Gamma_2$).

| $c\bar{c}g$ | $D^{*}$ | $L$ | $\Gamma_1$ | $\Gamma_2$ | $c\bar{c}g$ | $D^{*}$ | $L$ | $\Gamma_1$ | $\Gamma_2$ |
|------------|---------|-----|------------|------------|------------|---------|-----|------------|------------|
| 2$^-$      | 2$^+$   | S   | 0          | 120        | 2$^-$      | 2$^+$   | L   | 0          | 40         |
| 1$^+$      |         |     |            |            | 1$^+$      | 1$^+$   | P   | .3         | 10         |
| 0$^+$      |         |     |            |            | 0$^+$      | 0$^+$   | P   | 0          | 40         |
| 1$^-$      | 1$^+$   | S   | 20         | 30         | 1$^+$      | 2$^+$   | P   | 0          | 20         |
| 1$^+$      |         |     |            |            | 1$^+$      | 1$^+$   | P   | 20         | 120        |
| 0$^+$      |         |     |            |            | 0$^+$      | 0$^+$   | P   | 50         | 140        |
| 0$^-$      | 0$^+$   | S   | -          | 400        | 1$^+$      | 1$^+$   | P   | 0          | 30         |

3. Conclusions and Acknowledgements

The flux-tube model predicts a surprising stability of gluonic excitations in heavy mesons. Above the $D^{*2}$ threshold hybrids decay preferentially into $D^{*2}$ (with a width that is driven by the available phase space), instead of $DD, D^*D, D^*D^*$, perhaps explaining why hybrids have not yet been found experimentally.

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