Microscopic Model of Charmonium Strong Decays

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Although the spectra of heavy quarkonium systems has been successfully explained by certain QCD motivated potential models, their strong decays are difficult to deal with. We perform a microscopic calculation of charmonium strong decays using the same constituent quark model which successfully describes the $c\bar{c}$ meson spectrum. We compare the numerical results with the $^3P_0$ and the experimental data. Comparison with other predictions from similar models are included.

1 Introduction

Meson strong decay is a complex non-perturbative process that has not yet been described from QCD first principles. Instead, several phenomenological models have been developed to deal with this topic, like the $^3P_0$ model [1], the flux-tube model [2], or microscopic models (see Refs. [3–5]). The difference between the two approaches lies on the description of the $q\bar{q}$ creation vertex. While the $^3P_0$ model assumes that the $q\bar{q}$ pair is created from the vacuum, in the microscopic models the $q\bar{q}$ pair is created from the interquark interactions acting in the model.

The main ingredients in both calculations are the one-gluon exchange and the linear confinement. The differences lie in the Lorentz structure of the confinement being vector for Ref. [3, 4] and scalar for Ref. [5]. Phenomenology suggests that confinement has to be dominantly scalar in order to reproduce the hyperfine splitting observed in the charmonium sector. Strong decays may provide a new physics of information about the Lorentz structure.

In the present work, we generalize the schematic microscopic models of Refs. [3–5] using a more realistic constituent quark model which includes a linear screened confinement and studying the possible influence of the mixture of scalar and vector Lorentz structures.

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2 Constituent quark model

Constituent quark masses, coming from the spontaneous chiral symmetry breaking of the QCD Lagrangian, together with the perturbative one-gluon exchange (OGE) and the non-perturbative confining interaction are the main pieces of potential models. In a pure gluon gauge theory the potential energy of the $q\bar{q}$ pair grows linearly with the interquark distance. However, the presence of sea quarks may soften the linear potential. Using this idea, Vijande *et al.* [6] developed a model which is able to describe meson phenomenology from the light to the heavy quark sector. This model incorporates a confinement potential $V_{\rm CON}^{\rm scalar}(\vec{r}_{ij}) = V_{\rm CON}^{\rm vector}(\vec{r}_{ij}) = \left[-a_c(1-e^{-\mu_c r_{ij}})+\Delta\right](\vec{\lambda}_i^c \cdot \vec{\lambda}_j^c)$, with a mixture of a scalar and vector Lorentz structures $V_{\rm CON}(\vec{r}_{ij}) = a_s V_{\rm CON}^{\rm scalar}(\vec{r}_{ij}) + (1-a_s)V_{\rm CON}^{\rm vector}(\vec{r}_{ij})$.

To evaluate the strong decay amplitudes, we solve the Schrödinger equation using the Gaussian Expansion Method [7]. The model parameters can be found in Ref. [8].

3 A microscopic decay model

In the microscopic decay models the interaction Hamiltonian can be written as [5]

$$H_I = \frac{1}{2}\int d^3x d^3y \, J^a(\vec{x})K(|\vec{x}-\vec{y}|)J^a(\vec{y}). \tag{1}$$

The current J^a in Eq. (1) is assumed to be a color octet. The currents J (with the color dependence $\lambda^a/2$ factored out) are $J(\vec{x}) = \overline{\psi}(\vec{x})\Gamma\psi(\vec{x})$ where $\Gamma = \mathcal{I}, \gamma^0, \vec{\gamma}$. The kernels associated with the currents described before are $K(r) = -4a_s\left[-a_c(1-e^{-\mu_c r})+\Delta\right], +\frac{\alpha_s}{r}$ and $-\frac{\alpha_s}{r}$. For the vector Lorentz structure of the confinement we use as a kernel $K(r) = \pm(1-a_s)4\left[-a_c(1-e^{-\mu_c r})+\Delta\right]$, where ± refers to static and transverse vector terms, respectively.

4 Results and conclusions

The predictions for the total decay rates using the $^3P_0$ and the microscopic model are shown in Table 1. In general the total widths are lower in the microscopic model without improving the agreement with the experimental data.

It is difficult to compare our results with former calculations because either they are not fitted to the heavy quark sector [5] or does not include the same pieces of the current [3,4]. For the sake of the comparison we show in Table 2 the results of Ref. [4] together with our model prediction including only the static vector contribution and the full decay model. The basic difference between the two calculations is that in Ref. [4] the coupling with the meson-meson channels is treated nonperturbatively and this enhances the results when the threshold is close to the state. The predictions of the full decay model are clearly below the experimental data.

State	$^3P_0$	Mic.	Ref. [9]	Ref. [10]
$\psi(3770)$	26.4	19.0	27.6 ± 1.0	
$\psi(4040)$	111.0	39.1	80 ± 10	
$\psi(4160)$	115.7	32.7	103 ± 8	
$X(4360)$	113.7	102.2	$74 \pm 15 \pm 10$	
$\psi(4415)$	115.7	42.7	62 ± 20	119 ± 16
$X(4630)$	206.0	188.2	92^{+40+10}_{-24-21}	
$X(4660)$	134.8	142.2	$48 \pm 15 \pm 3$	

Table 1: Total decay rates, in MeV, predicted by the $^3P_0$ and the microscopic models.

Decay	Ref. [4]	j^0Kj^0	Mic.	Exp. [9]
$\psi(3770) \to DD$	20.1	29.8	19.0	27.6 ± 1
$\psi(4040) \to DD$	0.1	1.4	10.2	
$\psi(4040) \to DD^*$	33.0	25.2	18.7	
$\psi(4040) \to D^*D^*$	33.0	35.0	9.1	
$\psi(4040) \to D_sD_s$	8.0	0.3	1.1	
total	74.0	61.9	39.1	80 ± 10
$\psi(4160) \to DD$	3.2	25.0	17.0	
$\psi(4160) \to DD^*$	6.9	0.5	7.4	
$\psi(4160) \to D^*D^*$	41.9	21.3	5.3	
$\psi(4160) \to D_sD_s$	5.6	0.03	2.6	
$\psi(4160) \to D_sD_s^*$	11.0	0.6	0.4	
total	69.2	47.4	32.7	103 ± 8

Table 2: Decay rates, in MeV, reported in Ref. [4] and our decay rates taking into account only the static vector contribution and the full model.

Finally, in Table 3 we compare the experimental ratios of some charmonium decays with the prediction of the different models. None of them can explain the experimental data.

Therefore the full model has not solved the disagreement of the theoretical calculation with the data and more theoretical and experimental work is needed to solve the problem of the charmonium strong decay widths.

Acknowledgments

This work has been partially funded by Ministerio de Ciencia y Tecnología under Contract No. FPA2010-21750-C02-02, by the European Community-Research Infrastructure Integrating Activity 'Study of Strongly Interacting Matter' (HadronPhysics2 Grant No. 227431) and by the Spanish Ingenio-Consolider 2010 Program CPAN (CSD2007-00042).

State	Ratio	Cornell	j^0Kj^0	Mic.	$^3P_0$	Measured [9]
$\psi(4040)$	$D\overline{D}/D\overline{D}^*$	0.003	0.06	0.54	0.21	$0.24 \pm 0.05 \pm 0.12$
	$D^*\overline{D}^*/D\overline{D}^*$	1.00	1.39	0.48	3.70	$0.18 \pm 0.14 \pm 0.03$
$\psi(4160)$	$D\overline{D}/D^*\overline{D}^*$	0.08	1.17	3.23	0.27	$0.02 \pm 0.03 \pm 0.02$
	$D\overline{D}^*/D^*\overline{D}^*$	0.16	0.02	1.40	0.03	$0.34 \pm 0.14 \pm 0.05$
$X(4360)$	$D\overline{D}/D^*\overline{D}^*$	-	0.40	0.12	0.90	$0.14 \pm 0.12 \pm 0.03$
	$D\overline{D}^*/D^*\overline{D}^*$	-	0.08	0.64	0.92	$0.17 \pm 0.25 \pm 0.03$
$\psi(4415)$	$D\overline{D}/D^*\overline{D}^*$	-	1.54	1.10	0.46	$0.14 \pm 0.12 \pm 0.03$
	$D\overline{D}^*/D^*\overline{D}^*$	-	0.28	0.92	0.18	$0.17 \pm 0.25 \pm 0.03$

Table 3: Some ratios predicted theoretically by the $^3P_0$ and the microscopic models. The comparison with the experimental data is included.

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