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*Egypt. J. Phys.* **Vol. 48,** pp. 71-74 (2020)

**Egyptian Journal of Physics Science**

**http://ejfs.journals.ekb.eg/**

# Decays of Higher Charmonium above The $D\bar{D}$ threshold

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HADRONIC transitions of $J^{PC} = 1^{--}$higher charmonia are studied in the framework of the quark pair creation model. The modeldemonstrates its ability to reproduce observed decay widths and make predictions for the unobserved channels. Computed decay widths are in a good agreement with experimental data.

**Keywords**: Hadronic transitions, Quark pair creation model, Heavy quarkonium, Higher charmonia, Decay widths

## Introduction

The study of heavy quarkonium decays may be a sensible probe to understand the nonperturbative nature of quantum chromodynamics (QCD) at totally different energy regimes. The heavy meson is charmonium if it is Consisting of a charm quark (c) and an anti-charm quark (). The experimental facilities, such as CLEO, Belle, BABAR, CDF, D0, and BESIII, enable us to get on intensive experimental data in the charmonium (c) energy regime. This provides great opportunities to test and explore the nature of strong interactions in the heavy quark sector. Currently, BESIII takes data inthe c energy regime and it is easy to produce $J^{PC} = 1^{--}$ higher charmonia through $e^+e^-$ annihilations. These experimental facilities definitely help deepen our understanding of heavy quarkonium physicsand nonperturbative aspects of strong interaction, as well.

The charmonium resonances that are heavier than the threshold at 3.73 GeV are kinematically allowed to decay into D meson pairs and are commonly expected to be more extensive than the states under the threshold. In heavy systems, hadronic transitions function an important probe of their internal structures and help ascertain the understanding of light quark coupling with a significant degree of freedom.

Heavy quarkonium states can couple to intermediate heavy mesons through ‘the creation of a light quark-antiquark pair.The formalism, which incorporates intermediate heavy mesons within hadrons, is sometimes referred to as coupled-channel effects. For example, exploitation of the $^3P_0$ quark pair creation mechanism [1], intermediate hadron loop contributions are found to be essential to explain the suppression of dielectric decay widths of higher bottomonium [2].

The paper is organized as follows. In Sec. 2, we review the development of the $^3P_0$model and its application to hadron decays. Section 3 is devoted to discussing the results of (ψ(4040), (ψ(3770), (ψ(4160), and (ψ(4415). Finally, we give a summary in Sec. 4.

### *Theoretical Framework*

The most widely used model for studying open-flavor strong decays is the $^3P_0$or the quark pair creation (QPC) model. In this model, meson decay occurs when a quark–antiquark pair is produced from vacuum in a state suitable for quark rearrangement to occur, as shown in Fig. 1. The generated quark pair shares the quantum numbers of vacuum ($J^{PC} = 0^{++}$) (where P is the parity and C is the conjugation of charge) [3]. Therefore, it is referred to as the $^3P_0$ pair creation mechanism. The traditional $^3P_0$ model has been used over a large area in hadron spectroscopy and decays [2, 4, 5, 6]. In this model, the probability of generating independent q pairs is independent of the generation point distance from valence quarks. There is one non-specific parameter γ in the model that represents the possibility of creating a pair of anti-quarks from vacuum.

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Received :10/1/2020; accepted :8/3/2020

DOI :10.21608/ejphysics.2020.22265.1033

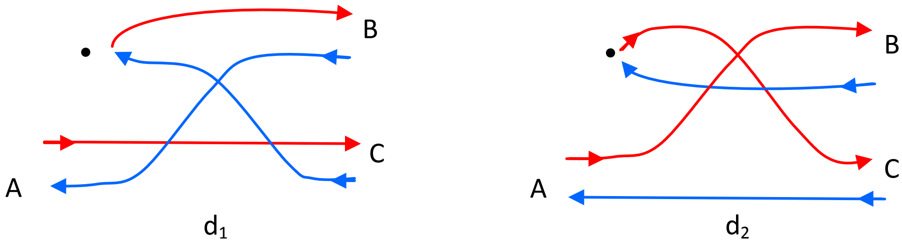

**Fig. 1.Two possible diagrams contributing to the meson decay (A→ BC) in the QPC model.**

In Ref. [7], general formulation of any decay is investigated. Here, we skip a lot of technical details in order to focus more on new developed aspects.

In a quark model of meson, the relative motion of the quark and antiquark is described by the wave function obtained by solving the Schrödinger equation with a Hamiltonian inspired by QCD. To find the overlap of the wave functions, we use simple harmonic oscillator (SHO) wave functions, which can be written in momentum space as

$$\varphi_{nr,lm}(p) = R_{nr,l}(p)\mathcal{Y}_l^m(p,\theta,\phi) \quad (1)$$

where $n_r$, $l$, and $m$ represent the radial, orbital, and magnetic quantum numbers, respectively. $=$ $p^l$) is the solid harmonic defined as a function of spherical harmonic. The radial wave function is given as

$$R_{nr,l}(p) = \sqrt{\frac{2n_r}{\Gamma\left(n_r+l+\frac{3}{2}\right)}}\beta^{-\left(l+\frac{3}{2}\right)}e^{-\frac{p^2}{2\beta^2}}L_{n_r}^{l+\frac{1}{2}}(p^2/\beta^2) \quad (2)$$

Where, is an oscillatory parameter and is the associated Laguerre polynomial.
For two-body $A\to BC$ decay, we define the transition amplitude as

$$\langle B\,C|H_I|A\rangle = 2\pi\sqrt{8E_AE_BE_C}\delta^4(p_i-p_f)\mathcal{M}^{m_{JA}m_{JB}m_{JC}} \quad (3)$$

while $E_A$, $E_B$, $E_C$ are the total energy for the meson (A), meson (B), and meson (C),respectively. The total energy E is given as

$$E = m + (P_{nrel}{}^2/2m) \quad (4)$$

Considering the standard non-relativistic phase space, we define the decay width in the center-of-mass (CM) frame as

$$\Gamma_{A\to B} = 2\pi\frac{m_B\,m_C}{(m_B+m_C)P_{nrel}}\left|M_{A\to B}\left(P_{nrel}\right)\right|^2 . \quad (5)$$

The non–relativistic momentum is given by

$$P_{nrel} = \frac{\sqrt{2m_Bm_C\left(m_A-m_B-m_C\right)}}{\sqrt{m_B+m_C}} . \quad (6)$$

The phase space is the most important factor to calculate the decay width. This expression is coded into routines in the symbolic computation package Mathematica.

## Results and Discussions

To get the decay widths, it would be better to analyze the dependence of the wave function on the oscillatory parameter $\beta$ in the case of SHO wave functions. For light qsystems, the best value of $\beta$ from spectroscopy and decays is 0.379 [4, 8]. However, for heavy qstates it is a bit larger and has a range $\beta$ = 0.4 to 0.6 in literature [9, 10, 11, 12] where the parameter $\beta$ relates to the size of the quark-antiquark bound state. To choose the same $\beta$ for initial and final mesons is quite reasonable [13] despite some predictions that each meson has its own effective $\beta$ [14]. Quark model studies show that the effective $\beta$ for higher c multiplets is smaller than the corresponding lower ones. This suggests that for higher charmonium states, the favorable value of $\beta$ should be around 0.4. We tune the parameter $\beta$ along with the coupling strength γ of the model. The coupling constant γ is fitted by choosing $\beta = 0.45$ for all involved mesons listed in Table 1 that agree with recent similar studies [10, 15, 16, 17]. In principle, there are two ways for using oscillatory parameter $\beta$ ;one can choose the same $\beta$ for all charmonium states for simplicity or different values of $\beta$ for initial and final mesons to be more accurate. In our work, we used the first and the second way and listed the computed results in Tables 2 and 3, respectively. For the sake of calculations, the experimental masses of mesons are considered.

**TABLE 1. All the mesons with the parameters studied.**

| ***State*** | | Expt. masses (MeV) | *β* | □ |
|---|---|---|---|---|
| ψ (3770) | $c\bar{c}$ $1\,^3D_1$ | **3773.13 ±0.35** | **0.45** | **0.23** |
| ψ (4040) | $c\bar{c}$ $3\,^3S_1$ | **4039±1** | **varying** | **0.293** |
| ψ (4160) | $c\bar{c}$ $2\,^3D_1$ | **4191±5** | | |
| ψ (4415) | $c\bar{c}$ $4\,^3S_1$ | **4421±4** | | |

All the widths are in units of MeV. For expressing the quantum numbers, we use the spectroscopic notation $n^{2S+1}L_J$.

**TABLE 2.**

| State | | | The Present work | Ref.[15] | Ref.[16] | Ref.[17] |
|---|---|---|---|---|---|---|
| ψ (3770) | $1^3D_1$ | 27±1 | 20.77 | 22.2 | 27 | 43 |
| ψ (4040) | $3^3S_1$ | 80±10 | 93.6 | 92.7 | 60 | 74 |
| ψ (4160) | $2^3D_1$ | 70±10 | 67.98 | 96.9 | 76 | 73.4 |
| ψ (4415) | $4^3S_1$ | 62±20 | 54.29 | 65.4 | -- | 45.6 |

The parameters used in our calculations are listed in Table 1. Table 2 shows fitted results by selecting the best values for the parameters in Table 1. We get a quite impressive agreement with the previous results from refs.[15- 17] and the experimental data ref. [18].

All the widths are in units of MeV. While **β** is varying any parameter, others are fixed.

Table 3 shows the fitted results with varying *β* for initial and final mesons. Wefound a significant agreement between the results and those gathered in Table 2, as well as the experimental data [18].

**TABLE 3.**

| *State* | $n^{3S+1}L_J$ | $\Gamma_{total.}$[ 18] | *The Present work* |
|---|---|---|---|
| ***ψ(3770)*** | $1^3D_1$ | *27±1* | 20 |
| ***ψ(4040)*** | $3^3S_1$ | *80±10* | 74.9 |
| ***ψ(4160)*** | $2^3D_1$ | *70±10* | 81.6 |
| ***ψ(4415)*** | $4^3S_1$ | *62±20* | 54.75 |

Error estimation in the hypothetical model is yet an open inquiry. It became an important debate among theoretical constructs over the last few years.

It is difficult to give the assessments of the decay width for (3D), (4D), and (5S) or higher ones because these states have not been tentatively entrenched. Henceforth, their masses are obscure.

## Summary

In the present study, we calculated the total decay width of higher charmonium around 4 GeV and propose the model to create a light meson for heavy quarkonium transition. This model is used to study higher charmonia vector decays into D meson. Moreover, computed decay widths are in excellent agreement with experimental data. We hope that our predictions may give helpful references for determining the characteristics of higher charmonium states in current and upcoming experiments

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## انحلالات ميزونات الشارمونيوم الاعلي من D

في هذه الدراسة ، تم حساب الاتساع الكلي لانحلال الشارمونيوم العالي حوالي 4 GeV ، واستخدمنا نموذج مقترح لإنشاء ميزون خفيف من تحلل الكواركونيوم الثقيل. يستخدم هذا النموذج لدراسة تحلل الشارمونيوم الى D meson. علاوة على ذلك ، فإن قيم الانحلالات المحسوبة تتفق بشكل ممتاز مع النتائج التجريبية. نأمل أن تعطي نتائجنا مراجع مفيدة لتحديد خصائص حالات اخرى للشارمونيوم في التجارب الحالية والقادمة.