## Quarkonium Wave Functions at the Origin

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## Abstract

We tabulate values of the radial Schrödinger wave function or its first nonvanishing derivative at zero quark-antiquark separation, for  $c\bar{c}$ ,  $c\bar{b}$ , and  $b\bar{b}$  levels that lie below, or just above, flavor threshold. These quantities are essential inputs for evaluating production cross sections for quarkonium states.

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Fragmentation of partons into quarkonium states recently has been recognized as an important component of quarkonium production in high-energy collisions [1]. Thorough investigation of this new source, and others, is made timely by the CDF Collaboration's observation that conventional sources substantially underestimate the yield of prompt  $J/\psi$  and  $\psi'$  in 1.8-TeV  $\bar{p}p$  collisions [2]. In the case of the  $\psi'$ , which is not fed by the cascade decay of the narrow  $\chi_c$  states, the observed cross section exceeds the calculated one by more than an order of magnitude.

Calculation of the production rate by fragmentation can be separated into a parton-level piece that can be evaluated using perturbative techniques and a hadronic piece expressed in terms of the quarkonium wave function. We have earlier tabulated the values at the origin of the radial wave function, or its first nonvanishing derivative, for narrow levels of the  $b\bar{c}$  ( $B_c$ ) system [3]. These have been used to estimate the  $B_c$  production rate [4]. Here we present the corresponding information for the  $c\bar{c}$  ( $J/\psi$ ) and  $b\bar{b}$  ( $\Upsilon$ ) families. Although many of these numbers have appeared in the literature when quarkonium spectroscopy was in flower, they usually were given implicitly in calculations of leptonic widths or similar observables. Our purpose here is to record the relevant properties of the wave functions of all the narrow levels in a form convenient for evaluating cross sections for quarkonium production.

We consider four functional forms for the potential that give reasonable accounts of the  $c\overline{c}$  and  $b\overline{b}$  spectra: the QCD-motivated potential given by Buchmüller and Tye [5], with

$$m_c = 1.48 \text{ GeV/}c^2 \quad m_b = 4.88 \text{ GeV/}c^2 \quad ;$$
 (1)

a power-law potential [6],

$$V(r) = -8.064 \text{ GeV} + (6.898 \text{ GeV})(r \cdot 1 \text{ GeV})^{0.1} , \qquad (2)$$

with

$$m_c = 1.8 \text{ GeV/}c^2 \quad m_b = 5.174 \text{ GeV/}c^2 \quad ;$$
 (3)

a logarithmic potential [7],

$$V(r) = -0.6635 \text{ GeV} + (0.733 \text{ GeV}) \log (r \cdot 1 \text{ GeV}) , \qquad (4)$$

with

$$m_c = 1.5 \text{ GeV/}c^2 \quad m_b = 4.906 \text{ GeV/}c^2 \quad ;$$
 (5)

and a Coulomb-plus-linear potential (the "Cornell potential") [8],

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2} \quad , \tag{6}$$

with

$$m_c = 1.84 \text{ GeV/}c^2 \quad m_b = 5.18 \text{ GeV/}c^2$$
 (7)

$$\kappa = 0.52 \quad a = 2.34 \text{ GeV}^{-1}$$
 (8)

For quarks bound in a central potential, it is convenient to separate the Schrödinger wave function into radial and angular pieces as  $\Psi_{n\ell m}(\vec{r}) = R_{n\ell}(r)Y_{\ell m}(\theta,\phi)$ , where n is the principal quantum number,  $\ell$  and m are the orbital angular momentum and its projection,  $R_{n\ell}(r)$  is the radial wave function, and  $Y_{\ell m}(\theta,\phi)$  is a spherical harmonic [9]. The Schrödinger wave function is normalized,  $\int d^3\vec{r} |\Psi_{n\ell m}(\vec{r})|^2 = 1$ , so that  $\int_0^\infty r^2 dr |R_{n\ell}(r)| = 1$ . The value of the radial wave function, or its first nonvanishing derivative at the origin,

$$R_{n\ell}^{(\ell)}(0) \equiv \left. \frac{d^{\ell} R_{n\ell}(r)}{dr^{\ell}} \right|_{r=0} , \qquad (9)$$

is required to evaluate production rates through parton fragmentation. The quantity  $|R_{n\ell}^{(\ell)}(0)|^2$  is presented for four potentials in Table I for the narrow charmonium levels and in Table II for the narrow Upsilon levels. For ease of reference, we reproduce in Table III our predictions [3] for the  $B_c$  wave functions, with some computational improvements in the entries for the Cornell potential. The strong Coulomb singularity of the Cornell potential is reflected in spatially smaller states.

In view of the efforts [10] to resolve the  $\psi'$  anomaly with cascades from above-threshold states, we quote values for the  $c\bar{c}$  3D, 3P, and 3S levels that lie near 3.8, 3.9, and 4.0 GeV/ $c^2$ , respectively, and for the  $b\bar{b}$  4F, 4D, 4P, and 4S levels that lie near 10.35, 10.45, 10.52, and

 $10.6 \text{ GeV/}c^2$ , respectively. It is likely that these will be significantly modified by coupled-channel effects [8,11].

If all the potentials describe the  $c\bar{c}$  and  $b\bar{b}$  observables, what accounts for the wide variation in the values of  $|R_{n0}(0)|^2$  and the corresponding quantities for orbital excitations? The leptonic decay rate of a neutral  $(Q\bar{Q})$  vector meson  $V^0$  is related to the Schrödinger wave function through [12,13]

$$\Gamma(V^0 \to e^+ e^-) = \frac{4N_c \alpha^2 e_Q^2}{3} \frac{|R_{n0}(0)|^2}{M_V^2} \left(1 - \frac{16\alpha_s}{3\pi}\right) , \qquad (10)$$

where  $N_c = 3$  is the number of quark colors,  $e_Q$  is the heavy-quark charge, and  $M_V$  is the mass of the vector meson. The QCD correction reduces the magnitudes significantly; the amount of this reduction is somewhat uncertain, because the first term in the perturbation expansion is large [14]. Each of the potentials we use corresponds to a particular interpretation of the radiative correction to the leptonic width. Similar effects may enter the connection between wave functions and fragmentation probabilities.

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TABLES

TABLE I. Radial wave functions at the origin and related quantities for  $c\bar{c}$  mesons.

Level		$ R_{n\ell}^{(\ell)}(0) ^2$		
	QCD (B–T), Ref. [5]	Power-law, Ref. [6]	Logarithmic, Ref. [7]	Cornell, Ref. [8]
1S	$0.810~{ m GeV^3}$	$0.999~\mathrm{GeV^3}$	$0.815~\mathrm{GeV^3}$	$1.454~\mathrm{GeV^3}$
2P	$0.075~\mathrm{GeV^5}$	$0.125~\mathrm{GeV^5}$	$0.078~{ m GeV^5}$	$0.131~{\rm GeV^5}$
2S	$0.529~\mathrm{GeV^3}$	$0.559~\mathrm{GeV^3}$	$0.418~\mathrm{GeV^3}$	$0.927~\mathrm{GeV^3}$
3D	$0.015~\mathrm{GeV^7}$	$0.026~\mathrm{GeV^7}$	$0.012~{ m GeV^7}$	$0.031~\mathrm{GeV^7}$
3P	$0.102~{ m GeV^5}$	$0.131~{ m GeV^5}$	$0.076~{ m GeV^5}$	$0.186~\mathrm{GeV^5}$
3S	$0.455~\mathrm{GeV^3}$	$0.410~\mathrm{GeV^3}$	$0.286~\mathrm{GeV^3}$	$0.791~{ m GeV^3}$

TABLE II. Radial wave functions at the origin and related quantities for  $b\bar{b}$  mesons.

Level		$ R_{n\ell}^{(\ell)}(0) ^2$		
	QCD (B–T), Ref. [5]	Power-law, Ref. [6]	Logarithmic, Ref. [7]	Cornell, Ref. [8]
1S	$6.477~\mathrm{GeV^3}$	$4.591~\mathrm{GeV^3}$	$4.916~\mathrm{GeV^3}$	$14.05~\mathrm{GeV^3}$
2P	$1.417~{ m GeV^5}$	$1.572~{ m GeV^5}$	$1.535~{ m GeV^5}$	$2.067~\mathrm{GeV^5}$
2S	$3.234~{\rm GeV^3}$	$2.571~\mathrm{GeV^3}$	$2.532~{ m GeV^3}$	$5.668~\mathrm{GeV^3}$
3D	$0.637~\mathrm{GeV}^7$	$0.892~\mathrm{GeV}^7$	$0.765  \mathrm{GeV}^7$	$0.860~\mathrm{GeV^7}$
3P	$1.653~{ m GeV^5}$	$1.660~\mathrm{GeV^5}$	$1.513~{ m GeV^5}$	$2.440~\mathrm{GeV^5}$
3S	$2.474~\mathrm{GeV^3}$	$1.858~\mathrm{GeV^3}$	$1.736~\mathrm{GeV^3}$	$4.271~\mathrm{GeV^3}$
4F	$0.414~{ m GeV^9}$	$0.627~\mathrm{GeV^9}$	$0.456~\mathrm{GeV^9}$	$0.563~\mathrm{GeV^9}$
4D	$1.191~{ m GeV}^7$	$1.396~{ m GeV}^7$	$1.119~{ m GeV}^7$	$1.636~\mathrm{GeV^7}$
4P	$1.794~{ m GeV^5}$	$1.593~{ m GeV^5}$	$1.377~{ m GeV^5}$	$2.700~\mathrm{GeV^5}$
4S	$2.146~\mathrm{GeV^3}$	$1.471~{ m GeV^3}$	$1.324~{ m GeV^3}$	$3.663~\mathrm{GeV^3}$
5F	$1.075~\mathrm{GeV^9}$	$1.302~{ m GeV^9}$	$0.894~\mathrm{GeV^9}$	$1.520~\mathrm{GeV^9}$
5D	$1.722~{ m GeV}^7$	$1.689~\mathrm{GeV}^7$	$1.289~\mathrm{GeV}^7$	$2.417~\mathrm{GeV}^7$
5P	$1.935~{ m GeV^5}$	$1.504~\mathrm{GeV^5}$	$1.252~{ m GeV^5}$	$2.917~\mathrm{GeV^5}$
5S	$1.956~\mathrm{GeV^3}$	$1.231~\mathrm{GeV^3}$	$1.077 \; {\rm GeV^3}$	$3.319  \mathrm{GeV^3}$

TABLE III. Radial wave functions at the origin and related quantities for  $c\bar{b}$  mesons.

Level		$ R_{n\ell}^{(\ell)}(0) ^2$		
	QCD (B–T), Ref. [5]	Power-law, Ref. [6]	Logarithmic, Ref. [7]	Cornell, Ref. [8]
1S	$1.642~{ m GeV^3}$	$1.710~{ m GeV^3}$	$1.508~{ m GeV^3}$	$3.184~\mathrm{GeV^3}$
2P	$0.201~{ m GeV^5}$	$0.327~\mathrm{GeV^5}$	$0.239~{ m GeV^5}$	$0.342~{ m GeV^5}$
2S	$0.983~\mathrm{GeV^3}$	$0.950~\mathrm{GeV^3}$	$0.770~\mathrm{GeV^3}$	$1.764~{ m GeV^3}$
3D	$0.055~\mathrm{GeV}^7$	$0.101~\mathrm{GeV}^7$	$0.055~\mathrm{GeV}^7$	$0.102~\rm GeV^7$
3P	$0.264~{ m GeV^5}$	$0.352~{ m GeV^5}$	$0.239~{ m GeV^5}$	$0.461~\mathrm{GeV^5}$
3S	$0.817~\mathrm{GeV^3}$	$0.680~\mathrm{GeV^3}$	$0.563~\mathrm{GeV^3}$	$1.444~\mathrm{GeV^3}$