Estimating the Branching Ratio for Bottomonium: Two Gluon and Two Photon Decay Widths

Vipin Naik N S[1, 2]*, Praveen P DSouza P[1], Antony Prakash Monteiro[1], and K. B. Vijaya Kumar[3]
[1]Department of Physics, St Philomena College, Darbe, Puttur - 574 202, INDIA
[2] Department of Physics, Mangalore University, Mangalagangothri, Mangalore - 574199, INDIA
[3]Deptartment of Physics, NMAM Institute of Technology, NITTE, Karkala - 574110, INDIA
** email:* aprakashmonteiro@gmail.com

Introduction

For heavy quarkonium decay and production, the rates can be factorized into a short-distance part, which can be calculated in QCD perturbatively, and a long-distance part, which are governed by nonperturbative QCD dynamics [1]. Therefore, radiative decays of bottomonium into charmonium may provide a useful test for NRQCD factorization, which is assumed to hold also for these specific exclusive processes, and may also provide some practical estimates for decays such as $\eta_b \rightarrow J/\psi\gamma$, which might be useful in search for the not yet discovered η_b meson. As a phenomenological model study, we further extend our calculation to the radiative decays of bottomonia into light mesons, two photon and two gluon decays. Other light mesons to be described by nonrelativistic $q\bar{q}$ $(q = u, d, s)$ bound states with constituent quark masses m_q (q = u, d) = 350 MeV, m_s = 500 MeV as in constituent quark models. These annihilation decays are known as the gluon rich channels, and regarded as a good place to investigate the interactions between quarks and gluons. We adopt the assumption that both heavy quarkonium and light mesons are described by the color-singlet nonrelativistic wave functions. Based on this assumption, we study $\Upsilon \rightarrow \chi_{cJ}\gamma$, $\Upsilon \rightarrow \eta_c\gamma$, $\Upsilon \rightarrow f_J\gamma$, $\Upsilon \rightarrow \eta\gamma$, $J/\psi \rightarrow f_J\gamma$, $J/\psi \rightarrow \eta\gamma$, $\chi_{bJ} \rightarrow J/\psi (\rho, \omega, \varphi)\gamma$ and $\eta_b \rightarrow J/\psi(\rho, \omega, \varphi)\gamma$ etc

By neglecting the relative quark momenta in the propagator term, the two-photon and two-gluon decay amplitude of heavy quarkonia states can be written as a local heavy quark field operator matrix element

Theoretical Background

The annihilation decays of bottomonium states into gluons and light quarks make significant contributions to the total decay. The annihilation decays allow us to determine wave function at the origin [2]. The annihilation decays of some $b\bar{b}$ states into photons can be used as a tool for the production and identification of the resonances.

(i) Two Photon Decays

Two-photon branching fraction for the charmonium provides a probe for the strong coupling constant at the bottomonium scale via the two-photon decay width. This can be utilized as a sensitive test for the corrections for the non-relativistic approximation in the potential models or in the effective field theories such as non-relativistic QCD (NRQCD). The two photon decay of P-wave bottomonium provide understanding of the nature of inter-quark forces and decay mechanisms [3].

$$\Gamma(n^3P_0 \rightarrow \gamma\gamma) = \frac{27e_c^4\alpha^2}{m_c^4}\left|R'_{np}(0)\right|^2\left(1 + \frac{0.2\alpha_s}{\pi}\right)$$

$$\Gamma(n^3P_2 \rightarrow \gamma\gamma) = \frac{36e_c^4\alpha^2}{5m_c^4}\left|R'_{np}(0)\right|^2\left(1 - \frac{16\alpha_s}{\pi}\right)$$

(ii) Two Gluon Decays

The even states in charge conjugation of quarkonium with $J \neq 1$ can annihilate into two gluons, much in the same way as they decay into two photons. The bottomonium states $^1S_0$, $^3P_0$, $^3P_2$, and $^1D_2$ can decay into two gluons, which account for a substantial portion of the hadronic decays for states below $b\bar{b}$ threshold. The two gluon decay widths are given by

$$\Gamma(n^3P_0 \rightarrow\ gg) = \frac{6\alpha_s^2}{m_c^4}\left|R^{|}_{np}(0)\right|^2(1+\frac{9.5\alpha_s}{\pi})$$

$$\Gamma(n^3P_2 \rightarrow\ gg) = \frac{8\alpha_s^2}{5m_c^4}\left|R^{|}_{np}(0)\right|^2(1-\frac{2.2\alpha_s}{\pi})$$

Results and Discussions

We consider the conventional nonrelativistic formalism for computations of the decay properties of the heavy flavour systems. In the traditional non-relativistic bound state calculation, the two-photon and two-gluon widths of quarkonium states depend on the ℓ^{th} derivatives of the radial wave function at the origin The ground states and first radical excitations of the P–wave bottomonia with orbital angular momentum L = 1 were estimated as 9856-10882 MeV, For the P-wave states, the annihilation decays to two-gluon or two-photon are generally suppressed than the S-wave. Therefore, all of the 1D, 2D and 1D states of bottomonium are expected to be narrow states.

$$\frac{\Gamma(\chi_{bo}(1^3P_0)\rightarrow\gamma\,\gamma}{\Gamma(\chi_{bo}(1^3P_0)\rightarrow g\,g} = 0.1299$$

$$\frac{\Gamma(\chi_{bo}(1^3P_2)\rightarrow\gamma\,\gamma}{\Gamma(\chi_{bo}(1^3P_2)\rightarrow g\,g} = 0.1406$$

$$\frac{\Gamma(\chi_{bo}(2^3P_0)\rightarrow\gamma\,\gamma}{\Gamma(\chi_{bo}(2^3P_0)\rightarrow g\,g} = 0.1244$$

$$\frac{\Gamma(\chi_{bo}(2^3P_2)\rightarrow\gamma\,\gamma}{\Gamma(\chi_{bo}(2^3P_2)\rightarrow g\,g} = 0.1184$$

$$\frac{\Gamma(\chi_{bo}(3^3P_2)\rightarrow\gamma\,\gamma}{\Gamma(\chi_{bo}(3^3P_2)\rightarrow g\,g} = 0.0845$$

$$\frac{\Gamma(\chi_{bo}(3^3P_0)\rightarrow\gamma\,\gamma}{\Gamma(\chi_{bo}(3^3P_0)\rightarrow g\,g} = 0.0279$$

Table 1: The two-photon decay widths (in keV) of the P wave bottomonium states $\Gamma_{\gamma\gamma}$ and $\Gamma^*_{\gamma\gamma}$ are present results without and with QCD correction respectively

State	J^{PC}	$\Gamma_{\gamma\gamma}$	$\Gamma^*_{\gamma\gamma}$
1^3P_0	0^{++}	0.128	0.141
2^3P_0	0^{++}	0.110	0.128
3^3P_0	0^{++}	0.091	0.116
1^3P_2	2^{++}	0.054	0.020
2^3P_2	2^{++}	0.038	0.015
3^3P_2	2^{++}	0.024	0.011

Table 1: The two gluon decay widths (in MeV) of the P wave bottomonium states Γ_{gg} and Γ^*_{gg} are present results without and with QCD correction respectively

State	J^{PC}	Γ_{gg}	Γ^*_{gg}
1^3P_0	0^{++}	0.985	1.514
2^3P_0	0^{++}	0.884	1.410
3^3P_0	0^{++}	0.685	1.012
1^3P_2	2^{++}	0.384	0.361
2^3P_2	2^{++}	0.321	0.311
3^3P_2	2^{++}	0.284	0.271

This study has discussed two-photon and two-gluon decay widths of p-wave heavy quarkonium states within the instanton induced potential from QCD vacuum. This formalism, which preserves the Lorentz covariance in the light-front framework, was applied to annihilations of the scalar and tensor quarkonia. To obtain the numerical results, we used the harmonic wave functions and fixed the parameters appearing in them. We considered the linear and HO potentials in the Hamiltonian and found that, when the parameters were fitted. The parameters corresponding to the linear potential were applied to estimate the relevant decay widths. The numerical results showed that, for the $b\bar{b}$ sector, all of the decay widths were in agreement with the experimental data and the major theoretical calculations. Relativistic corrections should be small for P wave bottomonium. Two-photon and two-gluon decays could be used to test QCD predictions and determination of α_s at the ground state of bottomonium mass spectra.

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