Annihilation decays of bottomonium

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Introduction

The bound state of a bottom quark b and its anti quark $\bar{b}$ known as bottomonium was first seen in the spectrum of $\mu\mu^-$ pairs produced in 400 GeV proton−nucleus collisions at Fermilab. It was dicovered as spin triplet states $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ by E288 collaboration at Fermilab[1, 2].

The spin-singlet state $\eta_b(1S)$ was discovered by the Babar Collaboration in 2008 and measured the mass of $\eta_b(1S)$ to be $M = 9388.9^{+3.1}_{-2.3}(stat) \pm 2.7(syst)$ MeV [3]. In an another measurement the BaBar found the mass of $\eta_b(1S)$ to be $M = 9394^{4.8}_{-2.3} \pm 2.7$ MeV. The CLEO collaboration measured the mass of $\eta_b(1S)$ to be 9391 ± 6.6 MeV[4]. The more precise measurement of mass of $\eta_b(1S)$ state is done by the Belle collaboration which obtained a value of $M = 9402.4 \pm 1.5 \pm 1.8$ MeV[5]. The $\eta_b(2S)$ was successfully observed by the CLEO collaboration in $\Upsilon(2S) \rightarrow \eta_b(2S)\gamma$ decays at a mass of $9974.6 \pm 2.3 \pm 2.1$ MeV[6]. The Belle collaboration has reported a signal for $\eta_b(2S)$ using the $h_b(2P) \rightarrow \eta_b(2S)\gamma$ at a mass of $9999.0 \pm 3.5^{2.8}_{1.9}$ MeV[6].

The BaBar collaboration first reported the evidence for the spin singlet P wave state $h_b(1P)$ in the transition $\Upsilon(3S) \rightarrow \pi^0 h_b(1P) \rightarrow \pi^0\gamma\eta_b(1S)$[6]. Later the Belle collaboration found $h_b(1P)$ through $\Upsilon(5S) \rightarrow h_b(1P)\pi^+\pi^-$ transition. The two triplet P-wave states $\chi_{bJ}(2P)$ and $\chi_{bj}(1P)$ with J=0,1,2 were discovered in radiative decays of the $\Upsilon(3S)$ and $\Upsilon(2S)$ in 1982 and 1983 respectively. The states $\chi_{bJ}(nP)$ were produced in the proton - proton collisions at the LHC at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector. In addition to this, a new state $\chi_{bJ}(3P)$ has been observed in both the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes. This state was confirmed by the D0 collaboration which observed the $\chi_{bJ}(3P)$ state in the $\Upsilon(1S)\gamma$ final state with mass of $10.551 \pm 0.014 \pm 0.017$ GeV[6].

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Theory

The annihilation decays of some bottomonium states into gluons and light quarks make significant contributions to the total decay width of the states. The annihilation decays allows us to determine wave function at very short range. The annihilation decays into leptons or photons can be used as a tool for the production and identification of resonances.

The annihilation decay rates into gluons and photons of the bottomonium states are given by

$$\Gamma(n\ ^3S_1 \rightarrow 3g) = \frac{10(\pi^2-9)\alpha_s^3}{81\pi m_b^2}|R_{nS}(0)|^2 \left(1 - \frac{4.9\alpha_s}{\pi}\right) \quad (1)$$

$$\Gamma(n\ ^3S_1 \rightarrow \gamma gg) = \frac{8(\pi^2-9)\alpha\alpha_s^2}{9\pi m_b^2}|R_{nS}(0)|^2 \left(1 - \frac{7.4\alpha_s}{\pi}\right) \quad (2)$$

$$\Gamma(n\ ^3S_1 \to 3\gamma) = \frac{4(\pi^2-9)\alpha\alpha_s^2}{3\pi m_b^2}|R_{nS}(0)|^2 \left(1 - \frac{12.6\alpha_s}{\pi}\right) \tag{3}$$

$$\Gamma(n\ ^1S_0 \to 2g) = \frac{2\alpha_s^2}{3m_b^2}|R_{nS}(0)|^2 \left(1 + \frac{4.4\alpha_s}{\pi}\right) \tag{4}$$

The decay of vector meson into charged leptons proceeds through the virtual photon ($q\bar{q} \to l^+l^-$ where $l = e^-, \mu^-, \tau^-$). The $^3S_1$ and $^3D_1$ states have quantum numbers of a virtual photon, $J^{PC} = 1^{--}$ and can annihilate into lepton pairs through one photon.

The leptonic decay width of the vector meson ($^3S_1$ bottomonium) including first order radiative QCD correction is given by

$$\Gamma(n\ ^3S_1 \to e^+e^-) = \frac{4\alpha^2 e_b^2 |R_{nS}(0)|^2}{M_{nS}^2}\left(1 - \frac{16\alpha_s}{3\pi}\right) \tag{5}$$

where $\alpha \approx \frac{1}{137}$ is the fine structure constant, M_{nS} is the mass of the decaying bottomonium state and $e_b = -1/3$ is the charge of the bottom quark in units of the electron charge.

The $q\bar{q}$ quark pair in charge conjugation even states with $J \neq 1$ can annihilate into two photons. The expressions for the decays of $n\ ^1S_0$ states into two photon with the first order QCD radiative correction are by

$$\Gamma(n\ ^1S_0 \to \gamma\gamma) = \frac{3e_b^4\alpha^2}{m_b^2}|R_{nS}(0)|^2 \left(1 - \frac{3.4\alpha_s}{\pi}\right) \tag{6}$$

Results and conclusion

We have calculated annihilation decay widths of bottomonium states. The calculated deacy widths are presented in table I. It is clear from the table that the calculated values agree very well with the other theoretical model. We have used $m_b = 5135$ MeV, $\alpha_s = 0.8$ in our calculation.

TABLE I: **Annihilation decay widths of bottomonium (in MeV) for various n values.**

transition	This work(keV)	Ref.[7]
$\eta_b(1S) \to gg$	19.56 MeV	20.18 MeV
$\eta_b(1S) \to \gamma\gamma$	0.75	0.69
$\eta_b(2S) \to gg$	11.04 MeV	10.64 MeV
$\eta_b(2S) \to \gamma\gamma$	0.286	0.36
$\eta_b(3S) \to gg$	8.23 MeV	7.94 MeV
$\eta_b(3S) \to \gamma\gamma$	0.254	0.27
$\Upsilon(1S) \to 3g$	39.73	41.63
$\Upsilon(1S) \to \gamma gg$	0.78	0.79
$\Upsilon(1S) \to 3\gamma$	3.02×10^{-6}	3.44×10^{-6}
$\Upsilon(1S) \to e^+e^-$	0.52	0.71
$\Upsilon(2S) \to \gamma gg$	0.56	0.37
$\Upsilon(2S) \to 3g$	23.873	24.25
$\Upsilon(2S) \to 3\gamma$	2.69×10^{-6}	2.00×10^{-6}
$\Upsilon(2S) \to e^+e^-$	0.335	0.37

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