Bottomonium at BABAR

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Abstract. Originally designed for CP violation studies in the B meson system, the B-Factories recently showed an exciting capability for improving our experimental knowledge in the field of hadron spectroscopy. Here I will present some of the most recent BABAR results concerning bottomonium spectroscopy. In particular, I’ll report the first observation of the ground state $\eta_b$ in $\Upsilon(nS) \rightarrow \gamma \eta_b$ and the results of an energy scan in the range of 10.54 to 11.20 GeV, that produced a new measurement of the $e^+e^- \rightarrow b\bar{b}$ cross section in the region of the $\Upsilon(4S)$ and candidate $\Upsilon(5S)$ and $\Upsilon(6S)$ resonances, with an integrated luminosity 30 times larger than the previous scans.

1. Introduction
In the last few years, quarkonium spectroscopy received significant contributions from the B-Facory experiments BABAR and Belle. This impact have been recently boosted by the decision of the BABAR Collaboration of running the PEP-II B-Factory at different Center of Mass (CM) energies, with the main goal of investigating bottomonium properties at a deeper level. About $\sim 28 \text{fb}^{-1}$ have been collected at the $\Upsilon(3S)$ resonance, providing the largest sample available worldwide at this CM energy. A sample of $\sim 14.5 \text{fb}^{-1}$ has been collected at the $\Upsilon(2S)$ resonance, and an energy scan of the region above the $\Upsilon(4S)$ resonance has been performed.

Here I will report some of the first results obtained in these unique samples: the discovery of the $\eta_b$ in $\Upsilon(3S) \rightarrow \gamma \eta_b$,[2] confirmed in $\Upsilon(2S) \rightarrow \gamma \eta_b$[3], and a measurement of the inclusive cross section $\sigma(e^+e^- \rightarrow b\bar{b})$ in the range of 10.54 to 11.20 GeV[4].

2. The $\eta_b$ Discovery
The $\eta_b(1S)$ (simply $\eta_b$ hereafter) is the ground state of the bottomonium spectrum, discovered by the BABAR collaboration in the $\Upsilon(3S) \rightarrow \eta_b \gamma$ decay channel, by exploiting a sample of $(109 \pm 1)$ million of $\Upsilon(3S)$. The mass of the $\eta_b$ was expected to lie around 9.4 GeV/c$^2$, hence the analysis consists of the search for a monochromatic photon of about 900 MeV in the $\Upsilon(3S)$ rest frame, accompanied by a set of charged tracks and electromagnetic clusters consistent with a hadronic $\eta_b$ decay.

Photons are identified as calorimeter clusters isolated from tracks and with a shape consistent with an electromagnetic shower, by requiring a lateral momentum [5] less than 0.55. A $\pi^0$ veto is also applied, by rejecting photons that, combined with other neutral clusters in the event, give an invariant mass consistent with a $\pi^0$ hypothesis within 15 MeV/c$^2$. In order to achieve a better resolution and a lower background, only the central part of the electromagnetic calorimeter ($0.762 < \cos(\theta_{\gamma,LAB}) < 0.890$) is used in this analysis. Hadronic $\eta_b$ decays are selected by

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1 A description of the BABAR detector can be found elsewhere [1].
requiring at least four tracks in the event. In order to reject the QED background, we require the ratio \( R_2 \) between the 0\( ^{th} \) and 2\( ^{nd} \) order Fox-Wolfram moments [6] to be less than 0.98. A selection is finally applied on the angle between the photon and the \( \eta_b \) thrust axis [7,8]. After this selection, the background is composed of a non-peaking contribution from light mesons decays and peaking contributions from the initial state radiation (ISR) process \( e^+e^- \rightarrow \gamma_{ISR}\eta \) and the bottomonium transitions \( \chi_{bJ}(2P) \rightarrow \gamma\eta \) \((J = 0, 1, 2)\). 

In figure 1 the photon spectrum after the selection is shown. A binned maximum likelihood (ML) fit of the spectrum is performed in the region between 0.5 and 1.1 GeV with four components: non-peaking background, \( \chi_{bJ}(2P) \rightarrow \gamma\eta \), \( \gamma_{ISR}\eta \) and the \( \eta_b \) signal. The non-peaking background is parameterized with a probability density function (PDF) given by \( \mathcal{P}(E_\gamma) = A \left( C + \exp \left[ -\alpha E_\gamma - \beta E_\gamma^2 \right] \right) \). The \( \chi_{bJ}(2P) \rightarrow \gamma\eta \) background is described by the superposition of three Crystal Ball (CB) PDFs [9], one for each \( J \) state. The ISR background is parameterized by a single CB PDF while the signal is described by the convolution of a Breit-Wigner and a CB PDF. The photon spectrum after non-peaking background rejection is also shown in figure 1. The fit yields 19200 ± 2000 ± 2100 signal events, corresponding to \( B(\eta \rightarrow \gamma \eta) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4} \). A significance of more than 10 standard deviations has been associated to this signal.

![Figure 1](image.png)

**Figure 1.** (a) Spectrum of \( E_\gamma \). The dashed line show the non-peaking background component. (b) Spectrum of \( E_\gamma \) after subtracting the non-peaking background component, with PDFs for \( \chi_{bJ}(2P) \) peak (solid), ISR \( \gamma\eta \) (dot), \( \eta_b \) signal (dash) and the sum of all three (solid).

The measured \( \eta_b \) mass is \( (9388.9^{+3.1}_{-2.3} \pm 2.7) \) MeV/c\(^2\), corresponding to a hyperfine splitting of \( M(\eta_b) - M(\eta) = (71.4^{+2.3}_{-3.1} \pm 2.7) \) MeV/c\(^2\). It is in agreement with recent lattice results [10], but a significant disagreement is found with respect to QCD calculations [11].

This result has been confirmed by a similar analysis performed on the \( \Upsilon(2S) \) data sample, looking for \( \Upsilon(2S) \rightarrow \eta_b\gamma \). In this case, a lower energy photon is present, implying a larger non-peaking background but also a better absolute energy resolution, allowing for a better separation of the signal from the other peaking components. We obtained \( M(\eta_b) = (9392.9^{+4.6}_{-4.8} \pm 1.8) \) MeV/c\(^2\) and \( B(\Upsilon(2S) \rightarrow \eta_b\gamma) = (4.2^{+1.1}_{-1.0} \pm 0.9) \times 10^{-4} \), with a 3.5\( \sigma \) signal significance. The corresponding fit is shown in figure 2.

**3. \( \sigma(e^+e^- \rightarrow b\bar{b}) \) scan above the \( \Upsilon(4S) \) resonance**

The recent discovery of exotic charmonium-like states [12] suggest the possibility of the existence of similar bottomonium-like states. A naive scaling of the new states, according to the typical mass difference between bottomonia and charmonia, suggests that new bottomonium states could lie in the region between the \( \Upsilon(4S) \) and the candidate \( \Upsilon(5S) \) and \( \Upsilon(6S) \). The BABAR Collaboration performed an energy scan of this region in order to investigate this possibility.
These components are also allowed to partially interfere. The results are quoted in Table 1.

The two resonances are modeled with two Breit-Wigner functions and a flat continuum is added.

$q$ residual of the $\Upsilon$ and 10.75 GeV are present, in agreement with theoretical predictions [17]. A fit for the extraction region makes difficult the interpretation of the results. Two evident structures between 10.60 and 10.75 GeV are present, in agreement with theoretical predictions [17]. A fit for the extraction of the $\Upsilon(5S)$ and $\Upsilon(6S)$ masses and widths has been also performed and is shown in figure 4. The two resonances are modeled with two Breit-Wigner functions and a flat continuum is added. These components are also allowed to partially interfere. The results are quoted in Table 1.
and show a significant disagreement with respect to the present world averages. Anyway, we want to stress that such a kind of naive parameterization is not suitable for describing the $b\bar{b}$ production near threshold, and more refined models should be used [18]. The disagreement between the current world average and our result, which is based on a more detailed scan, actually demonstrates that naive fits can provide inconsistent results and should be interpreted with care.

![Figure 3](image3.png)  
**Figure 3.** Measured $R_b$ as a function of the center of mass energy $\sqrt{s}$, with the position of the $e^+e^- \rightarrow B^{(*)}\overline{B}^{(*)}$ thresholds.

![Figure 4](image4.png)  
**Figure 4.** Fit of the $\Upsilon(5S)$ and $\Upsilon(6S)$ resonance shapes.

| Table 1. Results of the BABAR fit and comparison with the PDG world averages [19]. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                 | $\Upsilon(5S)$  | $\Upsilon(6S)$  | $\Upsilon(5S)$  | $\Upsilon(6S)$  |
| mass (GeV/$c^2$)                | 10.876 ± 0.002  | 10.996 ± 0.002  | 10.865 ± 0.008  | 11.019 ± 0.008  |
| width (MeV/$c^2$)               | 43 ± 4          | 37 ± 3          | 110 ± 13        | 79 ± 16         |

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