Recent results on bottomonium spectroscopy from BABAR

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DOI: http://dx.doi.org/10.5689/UA-PROC-2010-09/08

Recent results from the BABAR experiment on bottomonium spectroscopy are presented. The results include the first observation of the $\Upsilon(1^3D_J)$ in a hadronic decay channel, a study of the η_b using photon conversions, and searches for the as-yet-unseen $h_b(1P)$.

1 Introduction

The BABAR experiment operated at SLAC from 1999 to 2008. It collected data in the vicinity of the Υ system. The primary data sample (around 430 pb^{-1}) was collected on the $\Upsilon(4S)$ resonance and was used for studies of CP violation in B meson decays, for CKM physics, for charm meson physics, for τ lepton physics, and other studies. In the final two months of operation, the energy was lowered so that large samples on the $\Upsilon(3S)$ and $\Upsilon(2S)$ resonances could be collected. In particular, the world's largest sample of $\Upsilon(3S)$ events (by more than a factor of 10) was collected. 30 fb^{-1} were collected at the $\Upsilon(3S)$, corresponding to 120 million $\Upsilon(3S)$ decays. The corresponding figures for the $\Upsilon(2S)$ are 14 fb^{-1} and 100 million.

The spectrum of states below the open-flavor threshold is much richer for bottomonium than for charmonium, i.e., a lot more states are expected. The masses and branching fractions of these states provide important tests for QCD potential models and lattice QCD. Hadronic transitions between bottomonium states probe non-perturbative QCD.

Bottomonium states with orbital angular momentum $L = 0$ or 1 and total quark spin 1, namely the $\Upsilon(nS)$ and $\chi_{bJ}(nP)$ states, were observed in the 1970s and 1980s. There was then a long period during which no additional bottomonium states were discovered. This ended in 2004, when CLEO observed the $\Upsilon(1^3D_2)$ [1]. Subsequently, in 2008, BABAR observed the η_b [2]. Unlike charmonium, many bottomonium states below the open-flavor threshold have not yet been seen.

Three topics in bottomonium spectroscopy, based on the BABAR $\Upsilon(3S)$ sample, are presented here: a search for the η_b (the singlet $L = 0$ state of bottomonium) using $\gamma \to e^+e^-$ conversions, a search for the $h_b(1P)$ (singlet $L = 1$ state), which has not yet been seen, and the first observation of hadronic decays of the $\Upsilon(1^3D_2)$ (triplet $L = 2$) state. Besides the $\Upsilon(3S)$ sample, the η_b study makes use of the $\Upsilon(2S)$ sample. All results are preliminary.

2 Search for the η_b in photon conversions

The η_b was discovered [2] by *BABAR* in the recoil γ spectrum of $\Upsilon(3S) \to \gamma\eta_b$ decays. It was subsequently seen by *BABAR* in $\Upsilon(2S)$ decays [3] and confirmed by CLEO [4]. In the new study, a search for the η_b is made in the $\Upsilon(3S) \to \gamma\eta_b$ and $\Upsilon(2S) \to \gamma\eta_b$ channels using photon conversions, $\gamma \to e^+e^-$. Converted photons have 5 times better energy resolution than the calorimeter photons used in the previous η_b studies (5 MeV, rather than 25 MeV). Thus, the study based on converted photons can potentially help to improve the η_b mass measurement. The efficiency for converted photons is is lower than for calorimeter photons. Nonetheless an η_b signal on the order of 3 standard deviations is expected.

There are five monochromatic photons expected in the vicinity of the η_b signal photons: one from the signal photon itself, one from initial-state photon radiation (ISR) in $e^+e^- \to g_{ISR}\Upsilon(1S)$, and three from $\chi_{bJ} \to \gamma\Upsilon(1S)$ transitions ($J = 0, 1, 2$). After identifying $\gamma \to e^+e^-$ conversions with a conversion algorithm and applying vetoes against γ candidates from π^0 decay and other cuts, we perform a χ^2 fit to the γ recoil spectrum accounting for the five "peaking" components and a combinatoric background. The fit is made simultaneously to the $\Upsilon(3S)$ and $\Upsilon(2S)$ data with the η_b mass a fitted parameter.

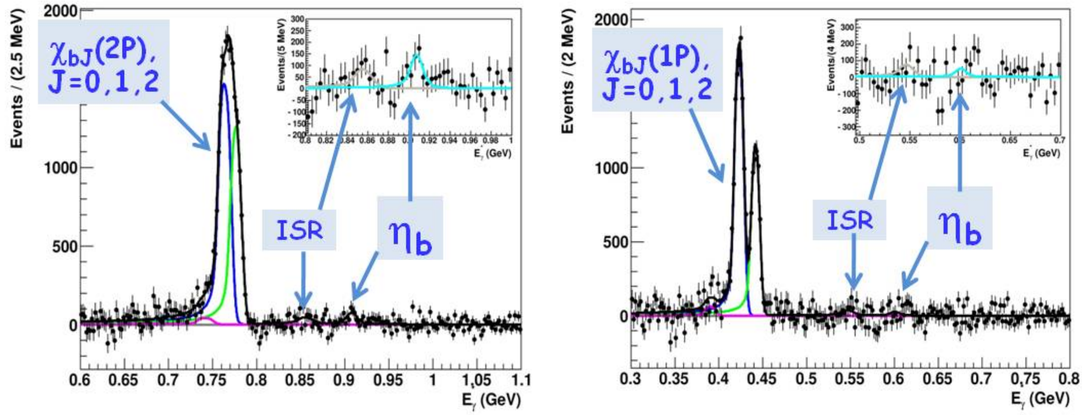


Figure 1: The γ recoil spectrum after subtraction of continuum background for the $\Upsilon(3S)$ (left) and $\Upsilon(2S)$ (right) data.

The results of the fit are shown in Fig. 1. The results are shown after subtraction of the continuum background term. The prominent peaks are from the $\chi_{bJ} \to \gamma\Upsilon(1S)$ transitions. The ISR and η_b contributions are indicated by the arrows. 773±220 η_b events are observed in the $\Upsilon(3S)$ decays (770 are expected), compared to 289 ± 281 in the $\Upsilon(2S)$ decays (390 expected). The combined η_b significance is 2.6 standard deviations including systematic uncertainties. Since the significance of the η_b observation is less than 3 standard deviations, it is difficult to make a conclusive statement about the fitted mass value: this is still under investigation.

As a side-benefit of this analysis, we obtain the world's best measurements for the separated $\Upsilon(nS) \to \gamma\chi_{bJ}[(n-1)P] \to \gamma\gamma\Upsilon(1S)$ branching fractions ($n = 2, 3$). For the $J = 1$ and 2 states, we improve the PDG averages by factors of about $2.5 - 3$ for the $\chi_{bJ}(2P)$ transitions and $3 - 4$ for the $\chi_{bJ}(1P)$ transitions.

3 Search for the $h_b(1P)$ state

The $h_b(1P)$ is a P-wave singlet state, as mentioned above. It is the hyperfine-splitting partner of the $\chi_{bJ}(1P)$ states. This hyperfine splitting is expected to be very small, leading to a firm expectation that the $h_b(1P)$ mass is close to 9900 MeV/c^2. Decays of the $\Upsilon(3S)$ to $\gamma h_b(1P)$, analogous to those discussed above the for η_b, are forbidden by charge-conjugation symmetry. The favored production mechanisms are hadronic: $\Upsilon(3S) \to \pi^0 h_b(1P)$ and $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$. Voloshin [5] predicts that the former decay dominates over the latter, while Kuang et al. [6] predict the opposite. However, there is much uncertainty in the predictions. The $h_b(1P)$ is expected to decay around 40% of the time to $\gamma\eta_b$. The monochromatic photon in this decay, of energy 490 MeV (resolution 25 MeV), can be used to help isolate an $h_b(1P)$ signal.

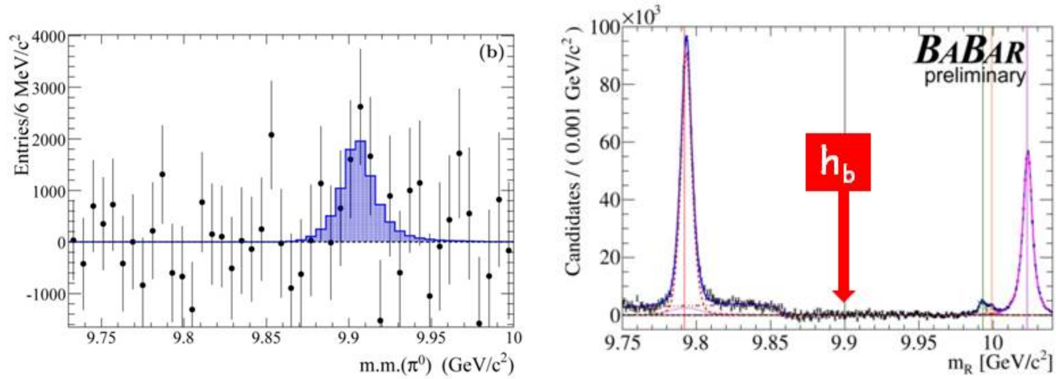


Figure 2: (left) The recoil spectrum against the π^0 in $\Upsilon(3S) \to \pi^0 + X$ events. (right) The recoil spectrum against the $\pi^+\pi^-$ pair in $\Upsilon(3S) \to \pi^+\pi^- + X$ events.

We search for the $h_b(1P)$ in the $\Upsilon(3S) \to \pi^0 h_b(1P)$ channel. We require the presence of a photon consistent with the $h_b(1P) \to \gamma\eta_b$ decay. $\pi^0 \to \gamma\gamma$ candidates are reconstructed, and cuts are applied to reduce background. The overall reconstruction efficiency is 22%. We perform a χ^2 fit to the recoil mass against the π^0, accounting for a smooth combinatorial background and a $h_b(1P)$ signal peak. The $h_b(1P)$ mass and yield are determined in the fit. The results after subtraction of the combinatoric background are shown in the left-hand plot of Fig. 2. The fitted mass of 9903 ± 4 MeV/c^2 agrees with the expectation of 9900 MeV/c^2. The statistical significance is 2.7 standard deviations including systematic uncertainties. We are currently refining the analysis.

We also search for the $h_b(1P)$ in the $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ channel. We select $\pi^+\pi^-$ pairs that originate at the interaction point. After removing obvious K_S^0 candidates, we plot the recoil mass against the $\pi^+\pi^-$ pair. We do not require a monochromatic photon from $h_b(1P) \to \gamma\eta_b$ decays for the $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ channel because this channel has less combinatoric background than the $\Upsilon(3S) \to \pi^0 h_b(1P)$ channel and this requirement is not necessary. The reconstruction efficiency is 42%. The results after subtraction of the combinatoric background are shown by the right-hand plot in Fig. 2. The large peak at around 9.80 GeV/c^2 is from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ transitions and that at around 10.02 GeV/c^2 from $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$ transitions. The less prominent structure just below 10.0 GeV/c^2 is from

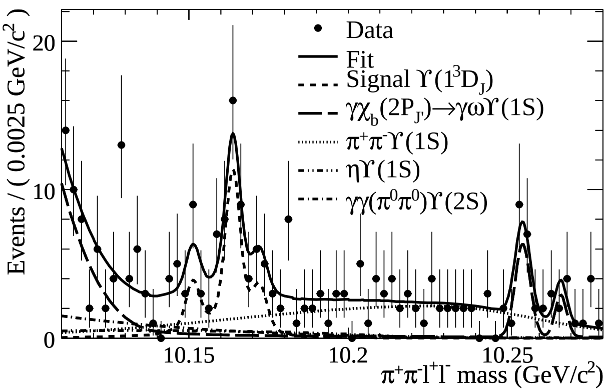
$\chi_{bJ}(2P) \to \pi^+\pi^-\chi_{bJ}(1P)$ transitions. At the value of 9.900 GeV/c^2 expected for the $h_b(1P)$ mass, there is no indication of a signal. Therefore we have no evidence for the $h_b(1P)$ in this channel.

4 Hadronic decays of the $\Upsilon(1^3D_2)$

The $\Upsilon(1^3D_2)$ state was first observed in 2004, by CLEO, as mentioned in the introduction. It was observed in the radiative $\Upsilon(1^3D_2) \to \gamma\gamma\Upsilon(1S)$ decay channel. The $\Upsilon(1^3D_J)$ is a triplet D-wave state. The signal seen by CLEO was consistent with a single state, interpreted to be the $J = 2$ member of the triplet.

In our study, we search for $\Upsilon(1^3D_J)$ states produced in the decay chain $\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_J) \to \gamma\gamma\pi^+\pi^-\Upsilon(1S)$, with $\Upsilon(1S) \to \ell^+\ell^-$ ($\ell = e,\ \mu$). The hadronic decay channel $\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)$ has been of interest for decades [7, 8, 9, 10]. Predictions for its branching fraction vary widely [8, 9, 10]. It provides better mass resolution than the radiative channel studied by CLEO and allows the L, J, and P quantum numbers, for which there is currently no experimental information, to be tested, through measurement of the angular distributions of the $\pi^\pm$ and $\ell^\pm$.

To search for $\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_J) \to \gamma\gamma\pi^+\pi^-\Upsilon(1S)$ decays, we require exactly four charged tracks in an event, two of which are identified as pions with opposite charge and the other two as either an e^+e^- or $\mu^+\mu^-$ pair. The $\Upsilon(1S)$ candidate is selected by requiring $-0.35 < m_{e^+e^-} - m_{\Upsilon(1S)} < 0.2$ GeV/c^2 or $|m_{\mu^+\mu^-} - m_{\Upsilon(1S)}| < 0.2$ GeV/c^2. The pion pair is combined with the $\Upsilon(1S)$ candidate to form a $\Upsilon(1^3D_J)$ candidate. Two photons consistent with the expected decay chain are required. The $\Upsilon(1^3D_J)$ candidate is combined with the two photons to form a $\Upsilon(3S)$ candidate. The CM momentum and energy of the $\Upsilon(3S)$ are required to be consistent with zero and $\Upsilon(3S)$ mass, respectively. The overall selection efficiency is around 26%.



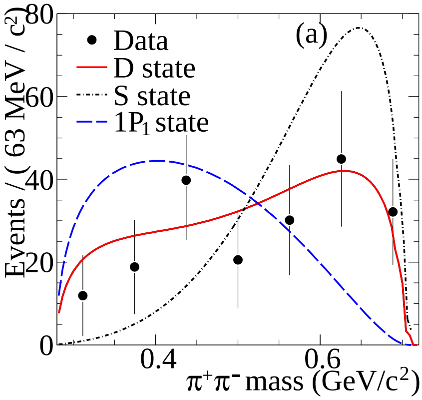


Figure 3: (left) The recoil spectrum against the π^0 in $\Upsilon(3S) \to \pi^0 + X$ events. (right) The recoil spectrum against the $\pi^+\pi^-$ pair in $\Upsilon(3S) \to \pi^+\pi^- + X$ events.

We apply an unbinned maximum likelihood fit to the selected events. The fit has a component for each of the three $\Upsilon(1^3D_J)$ signal states as well as several background categories. The result of the fit is shown in the left-hand portion of Fig. 3. We obtain a yield of

$33.9^{+8.2}_{-7.5}$ $\Upsilon(1^3D_2)$ events, corresponding to a significance of 5.8 standard deviations including systematic uncertainties. The significances of the $\Upsilon(1^3D_1)$ and $\Upsilon(1^3D_3)$ states are less than 2 standard deviations after systematics are included. We determine the $\Upsilon(1^3D_2)$ mass to be $10164.5 \pm 0.8 \pm 0.5$ MeV/c^2, which improves the CLEO result by almost a factor of two. We determine the $\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)$ branching fraction to be $0.66\,^{+0.15}_{-0.14} \pm 0.06\%$, which lies between the predictions of about 0.2% from Ref. [9] and 2% from Ref. [10].

The right-hand portion of Fig. 3 shows the $\pi^+\pi^-$ mass distribution for events in the $\Upsilon(1^3D_J)$ signal region $10.140 < m_{\pi^+\pi^-\ell^+\ell^-} < 10.178$ GeV/c^2. Shown in comparison are the expectations for the decay of a D, S, or $^1P_1$ bottomonium state to $\pi^+\pi^-\Upsilon(1S)$. The resulting χ^2 probabilities of 84.6%, 3.1%, and 0.3%, respectively, strongly favor the D state. This confirms the orbital angular momentum quantum number of the observed state. Similarly, we examine the distribution of the angle χ between the $\ell^+\ell^-$ and $\pi^+\pi^-$ planes in the $\Upsilon(1^3D_2)$ rest frame and find consistency with the expected assignments $J = 2$ and $P = -1$ (total spin and parity).

5 Summary

In summary, *BABAR* collected the world's largest sample of $\Upsilon(3S)$ events in 2008, during the last two months the detector was in operation. A large sample of $\Upsilon(2S)$ events was collected in addition. Three studies of bottomonium spectroscopy based on these data are presented here. Using converted photons in $\Upsilon(3S)$ and $\Upsilon(2S)$ decays to $\gamma\eta_b$, an η_b signal with a significance of around 2.6 standard deviations (with systematics) is observed. This measurement may allow improvements in the η_b mass determination. We improve the world measurements of the $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ and $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ branching fractions (separated by J) by factors of 3 to 4. We find evidence for the as-yet-unseen $h_b(1P)$ state at the level of about 2.7 standard deviations (including systematics) in the $\Upsilon(3S) \to \pi^0 h_b(1P)$ channel. We have made the first observation of hadronic decays of the $\Upsilon(1^3D_2)$ state. The significance is 5.8 standard deviations including systematics. We improve the mass measurement of the $\Upsilon(1^3D_2)$ by a factor of two and provide the first tests of its quantum numbers.

References

[1] G. Bonvicini *et al.* (CLEO Collaboration), Phys. Rev. D **70**, 032001 (2004).

[2] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **101** (2008) 071801.

[3] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **103** (2009) 161801.

[4] G. Bonvicini *et al.* (CLEO Collaboration), Phys. Rev. D **81** (2010) 031104.

[5] M.B. Voloshin, Sov. J. Nucl. Phys. **43** (1986) 1011.

[6] Y.-P. Kuang, S.F. Tuan, and T.-M. Yan, Phys. Rev. D **37** (1988) 1210.

[7] W. Kwong and J. L. Rosner, Phys. Rev. D **38**, 279 (1988).

[8] Y.-P. Kuang and T.-M. Yan, Phys. Rev. D **24**, 2874 (1981).

[9] P. Moxhay, Phys. Rev. D **37**, 2557 (1988).

[10] P. Ko, Phys. Rev. D **47**, 208 (1993).