Evidence for the $h_b(1P)$ meson in the decay $\Upsilon(3S) \to \pi^0 h_b(1P)$


Work supported in part by US Department of Energy contract DE-AC02-76SF00515.
(The BABAR Collaboration)

1Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS-IN2P3, F-74941 Annecy-Le-Vieux, France
2Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
3INFN Sezione di Bara®; Dipartimento di Fisica, Università di Barab®, I-70126 Bari, Italy
4University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
7University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
8Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
9Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
10University of California at Irvine, Irvine, California 92697, USA
11University of California at Riverside, Riverside, California 92521, USA
12University of California at Santa Barbara, Santa Barbara, California 93106, USA
13University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
14California Institute of Technology, Pasadena, California 91125, USA
15University of Cincinnati, Cincinnati, Ohio 45221, USA
16University of Colorado, Boulder, Colorado 80309, USA
17Colorado State University, Fort Collins, Colorado 80523, USA
18Technische Universität Dresden, Fakultät Physik, D-01221 Dresden, Germany
19Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
20Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
21University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
22INFN Sezione di Ferrara®; Dipartimento di Fisica, Università di Ferrara®, I-44100 Ferrara, Italy
23INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
24University of Hawaii, Honolulu, Hawaii 96822, USA
25University of Iowa, Iowa City, Iowa 52242, USA
26University of Kentucky, Lexington, Kentucky 40506, USA
27University of Kansas, Lawrence, Kansas 66045, USA
28Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B. P. 34, F-91898 Orsay Cedex, France
29Lawrence Livermore National Laboratory, Livermore, California 94550, USA
30Imperial College London, London, SW7 2AZ, United Kingdom
31University of Iowa, Iowa City, Iowa 52242, USA
32University of Kansas, Lawrence, Kansas 66045, USA
33Johns Hopkins University, Baltimore, Maryland 21218, USA
34Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B. P. 34, F-91898 Orsay Cedex, France
35Lawrence Livermore National Laboratory, Livermore, California 94550, USA
36University of Liverpool, Liverpool L69 7ZE, United Kingdom
37Queen Mary, University of London, London, E1 4NS, United Kingdom
38University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
39University of Louisville, Louisville, Kentucky 40292, USA
40Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
41University of Manchester, Manchester M13 9PL, United Kingdom
42University of Maryland, College Park, Maryland 20742, USA
43University of Massachusetts, Amherst, Massachusetts 01003, USA
44Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
Using a sample of 122 million $\Upsilon(3S)$ events recorded with the BABAR detector at the PEP-II asymmetric-energy $e^{+}e^{-}$ collider at SLAC, we search for the $h_{b}(1P)$ spin-singlet partner of the $P$-wave $\chi_{b}(1P)$ states in the sequential decay $\Upsilon(3S) \rightarrow \pi^0 h_{b}(1P)$, $h_{b}(1P) \rightarrow \gamma \eta_b(1S)$. We observe an excess of events above background in the distribution of the recoil mass against the $\pi^0$ at mass $9902 \pm 4\text{(stat.)} \pm 1\text{(syst.)} \text{MeV}/c^2$. The width of the observed signal is consistent with experimental resolution, and its significance is $3.0 \sigma$, including systematic uncertainties. We obtain the value $(3.7\pm 1.1\text{ (stat.)} \pm 0.7\text{ (syst.)}) \times 10^{-4}$ for the product branching fraction $\mathcal{B}(\Upsilon(3S) \rightarrow \pi^0 h_{b}) \times \mathcal{B}(h_{b} \rightarrow \gamma \eta_b)$.


To understand the spin dependence of $q\bar{q}$ potentials for heavy quarks, it is essential to measure the hyperfine mass splitting for $P$-wave states. In the non-relativistic approximation, the hyperfine splitting is proportional to the square of the wave function at the origin, which is expected to be non-zero only for $L = 0$, where $L$ is the orbital angular momentum quantum number of the $q\bar{q}$ system. For $L = 1$, the splitting between the spin-singlet ($1^P_1$) and the spin-averaged triplet state ($3^P_J$) is expected to be $\Delta M_{\text{HF}} = M(3^P_J) - M(1^P_1) \sim 0$. The $1^P_1$ state of bottomonium, the $h_{b}(1P)$, is the axial vector partner of the $P$-wave $\chi_{b,P}(1P)$ states. Its expected mass, computed as the spin-weighted center of gravity of the $\chi_{b,P}(1P)$ states [1], is $8989.87 \pm 0.27 \text{MeV}/c^2$. Higher-order corrections might cause a small deviation from this value, but a hyperfine splitting larger than $1 \text{MeV}/c^2$ might be indicative of a vector component in the confinement potential [2]. The hyperfine splitting for the charmonium $1^P_1$ state $h_c$ is measured by the BES and CLEO experiments [3, 4] to be $\sim 0.1 \text{MeV}/c^2$. An even smaller splitting is expected for the much heavier bottomonium system [2].
The $h_b(1P)$ state is expected to be produced in $\Upsilon(3S)$ decay via $\pi^0$ or di-pion emission, and to undergo a subsequent $E1$ transition to the $\eta_b(1S)$, with branching fraction (BF) $\mathcal{B}(h_b(1P) \to \gamma\eta_b(1S)) \sim (40 - 50\%)$ [2, 3]. The isospin-violating decay $\Upsilon(3S) \to \pi^0 h_b(1P)$ is expected to have a BF of about 0.1% [4, 5], while theoretical predictions for the transition $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ range from $\sim 10^{-4}$ [6] up to $\sim 10^{-3}$ [7]. The CLEO experiment reported the 90% confidence level (C.L.) limit $\mathcal{B}(\Upsilon(3S) \to \pi^0 h_b(1P)) < 0.27\%$ [7] based on fewer than 0.5 million $\Upsilon(3S)$ events.

In this paper, we report evidence for the $h_b(1P)$ state in the decay $\Upsilon(3S) \to \pi^0 h_b(1P)$. The data sample used was collected with the BABAR detector [8] at the PEP-II asymmetric-energy $e^+e^-$ collider at the SLAC National Accelerator Laboratory and corresponds to 28 fb$^{-1}$ of integrated luminosity at a center-of-mass (CM) energy of 10.355 GeV, the mass of the $\Upsilon(3S)$ resonance. This sample contains $(122 \pm 11)$ million $\Upsilon(3S)$ events. Detailed Monte Carlo (MC) simulations [12] of samples of exclusive $\Upsilon(3S) \to \pi^0 h_b(1P)$, $h_b(1P) \to \gamma\eta_b(1S)$ decays (where the $h_b(1P)$ and $\eta_b(1S)$ are hereafter referred to as the $h_b$ and the $\eta_b$), and of inclusive $\Upsilon(3S)$ decays, are used in this study. These samples correspond to 34,000 signal and 215 million $\Upsilon(3S)$ events, respectively.

The trajectories of charged particles are reconstructed using a combination of five layers of double-sided silicon strip detectors and a 40-layer drift chamber, both operating inside the 1.5-T magnetic field of a superconducting solenoid. Photons are detected, and their energies measured, with a CsI(Tl) electromagnetic calorimeter (EMC), also located inside the solenoid. The BABAR detector is described in detail elsewhere [11].

The signal for $\Upsilon(3S) \to \pi^0 h_b$ decays is extracted from a fit to the inclusive recoil mass distribution against the $\pi^0$ candidates ($m_{\text{recoil}}(\pi^0)$). It is expected to appear as a small excess centered near 9.9 GeV/c$^2$ on top of the very large non-peaking background produced from continuum events ($e^+e^- \to q\bar{q}$ with $q = u, d, s, c$) and bottomonium decays. The recoil mass, $m_{\text{recoil}}(\pi^0) = \sqrt{(E_{\text{beam}} - E^*(\pi^0))^2 - p^2(\pi^0)^2}$ (where $E_{\text{beam}}$ corresponds to the sum of the beam particle CM energies, in the $e^+e^-$ CM frame (denoted by the asterisk)) We enhance the sensitivity of the search for the $h_b$ by exploiting the fact that the $h_b$ is expected to decay predominantly to $\gamma\eta_b$, and so require a reconstructed photon consistent with this decay. The precise measurement of the $\eta_b$ mass [13] defines a restricted energy range for a photon candidate compatible with this subsequent $h_b$ decay. A similar approach led to the observation by CLEO-c, and then by BES, of the $h_b$ in the decay chain $\psi(2S) \to h_b \pi^0 \to \eta_b\gamma\pi^0$ [3, 7], where the $\eta_b$ was identified both exclusively (by reconstructing a large number of hadronic modes) and inclusively.

The photon from $h_b \to \gamma\eta_b$ decay is monochromatic in the $h_b$ rest-frame and is expected to peak at $\sim 490$ MeV in the $e^+e^-$ CM frame, with a small Doppler broadening that arises from the motion of the $h_b$ in that frame; the corresponding energy resolution is expected to be $\sim 25$ MeV. The Doppler broadening is negligible compared with the energy resolution. Figure 1 shows the reconstructed CM energy distribution of such candidate photons in the region 250-1000 MeV for simulated $\Upsilon(3S) \to \pi^0 h_b$, $h_b \to \gamma\eta_b$ events before the application of selection criteria; the signal photon from $h_b \to \gamma\eta_b$ decay appears as a peak on top of a smooth background. We select monochromatic photon candidates with CM energy in the range 420-540 MeV (indicated by the shaded region in Fig. 1).

![FIG. 1: The reconstructed CM energy distribution of the candidate photon ($\gamma$) in simulated $\Upsilon(3S) \to \pi^0 h_b(1P), h_b(1P) \to \gamma\eta_b(1S)$ events. The shaded region indicates the selected $E^*(\gamma)$ signal region.](image)

We employ a simple set of selection criteria to suppress backgrounds while retaining a high signal efficiency. These selection criteria are chosen by optimizing the $S/\sqrt{B}$ ratio between the expected signal yield ($S$) and the background ($B$). The $\Upsilon(3S) \to \pi^0 h_b$, $h_b \to \gamma\eta_b$ MC signal sample is used in the optimization, while a small fraction (9%) of the total data sample is used to model the background. We estimate the contribution $B$ in the signal region, defined by $9.85 < m_{\text{recoil}}(\pi^0) < 9.95$ GeV/c$^2$, using the sidebands of the expected $h_b$ signal region, $9.80 < m_{\text{recoil}}(\pi^0) < 9.85$ GeV/c$^2$ and $9.95 < m_{\text{recoil}}(\pi^0) < 10.00$ GeV/c$^2$.

The decay of the $\eta_b$ is expected to result in high final-state track multiplicity. Therefore, we select a hadronic event candidate by requiring that it have four or more charged-particle tracks, and that the ratio of the second to zeroth Fox-Wolfram moments [14] be less than 0.6 [15].

For a given event, we require that a primary vertex
be found and fitted successfully from all charged-particle tracks in the event. We then constrain the candidate photons in that event to originate from that vertex.

A photon candidate is required to deposit a minimum laboratory energy of 50 MeV into a contiguous EMC crystal that is isolated from all charged-particle tracks in that event. To ensure that the cluster shape is consistent with that for an electromagnetic shower, its lateral angle is within 15 MeV/c² from the laboratory energy of 50 MeV into a contiguous EMC crystal. To search for an 

\[ \pi^0 \rightarrow \gamma\gamma \]

The histogram representing background is obtained by subtracting the \( \pi^0 \)-signal from the total distribution. For both signal and background data the qualitative changes in shape over the full range of \( m_{\text{recoil}}(\pi^0) \) are quite well reproduced by the MC. However, the \( \pi^0 \) signal distribution from data is slightly broader, and the peak mass value slightly higher, than for the simulation. The \( m(\gamma\gamma) \) background shape also differs between data and MC. To address these differences, the MC \( \pi^0 \) signal is displaced in mass and smeared by a double Gaussian function with different mean and width values; the MC background distribution is weighted according to a polynomial in \( m(\gamma\gamma) \). The signal-shape and background weighting-parameter values are obtained from a fit to the \( m(\gamma\gamma) \) distribution in data for the full range of \( m_{\text{recoil}}(\pi^0) \). At each step in the fitting procedure, the \( \pi^0 \)-signal and background distributions are normalized to unit area, and a \( \chi^2 \) between a linear combination of these MC histograms and the \( m(\gamma\gamma) \) distribution in data is computed. The result, shown in Fig. 2, indicates that the fit function provides an adequate description of the data (\( \chi^2/NDF=1446/1433 \); \( NDF= \) Number of Degrees of Freedom). The background distribution exhibits a small peak at the \( \pi^0 \) mass, due to interactions in the detector material of the type \( n\pi^+ \rightarrow p\pi^0 \) or \( p\pi^- \rightarrow n\pi^0 \) that cannot be truth-matched. The normalization of this background to the non-peaking background is obtained from the MC simulation, which incorporates the results of detailed studies of interactions in the detector material performed using data [18]. This peak is displaced and smeared in the same way as the primary \( \pi^0 \) signal.

The fits to the individual \( m(\gamma\gamma) \) distributions are per-
formed with the smearing and weighting parameters fixed to the values obtained from the fit shown in Fig. 2. In this process, the MC signal and background distributions for each $m_{\text{recoil}}(\pi^0)$ interval are shifted, smeared, and weighted using the fixed parameter values, and then normalized to unit area. Thus, only the signal and background normalizations are free parameters in each fit. The $\chi^2$-fit to the data then gives the value and uncertainty of the coefficient multiplying the $\pi^0$-signal histogram as the number of $\pi^0$ events and its uncertainty. The fits to the 90 $m(\gamma\gamma)$ distributions provide good descriptions of the data, with an average $\langle \chi^2/NDF \rangle = 0.98 \pm 0.03$ ($NDF=1448$), where the value $\pm 0.03$ is the r.m.s. of the distribution. We verify that the fitted $\pi^0$ yield is consistent with the number of truth-associated $\pi^0$'s in MC to ensure that the $\pi^0$ selection efficiency is well-determined using truth-matching, and to check the validity of the $\pi^0$-signal extraction procedure.

Figure 3 shows the $m_{\text{recoil}}(\pi^0)$ distribution obtained in data by applying the $\pi^0$-signal extraction procedure. To search for an $h_b$ signal, we perform a binned $\chi^2$ fit to this spectrum using a fit function that contains signal and background contributions. The signal component is parametrized with the sum of two Crystal Ball [19] functions with parameter values determined from signal $\Upsilon(3S) \rightarrow \pi^0 h_b$ MC events. The background function is obtained from the background distribution of an inclusive MC sample that is weighted to accurately model the distribution in data. The weighting function is a fifth order polynomial with parameters set from a fit of the ratio of the $m_{\text{recoil}}(\pi^0)$ distributions in data and MC excluding the $h_b$ signal region (9.87–9.93 GeV/$c^2$). We obtain a corrected MC background distribution by applying this weight over the full range of $m_{\text{recoil}}(\pi^0)$.

We fit the corrected MC background distribution with a sixth order polynomial function. To improve sensitivity, the background function is fixed in the fit to data. All the parameters of the $h_b$ signal lineshape except the peak position and yield are fixed. The number of $h_b$ events obtained from the fit is $9145 \pm 2804$, and the $h_b$ fitted mass value is $m = 9902 \pm 4$ MeV/$c^2$. The distribution of the normalized residuals is described by a Gaussian function with mean and width values consistent with zero and one, respectively; this confirms that the uncertainties associated with the individual $\pi^0$ signals are reliable.

In order to determine the statistical significance of the signal we repeat the fit with the $h_b$ mass fixed to the center of gravity of the $\chi_{bJ}(1P)$ states, $m = 9900$ MeV/$c^2$. The signal yield obtained from this fit is $8959 \pm 2796$. The statistical significance of the signal is calculated from the square-root of the difference in $\chi^2$ for this fit with and without a signal component; this gives a value of 3.2 standard deviations. Figure 4 represents the results of a scan performed as a function of the assumed $h_b$ mass. Each point in this figure corresponds to the fitted signal yield with the $h_b$ mass parameter fixed.

![Figure 3](image_url)

**FIG. 3**: (a) The $m_{\text{recoil}}(\pi^0)$ distribution in the region $9.73 < m_{\text{recoil}}(\pi^0) < 10$ GeV/$c^2$ for data (points); the solid curve represents the fit function described in the text. The normalized residuals are shown underneath. (b) (inset) Expanded view of the signal region; the dashed curve represents the background function. (c) The $m_{\text{recoil}}(\pi^0)$ spectrum after subtracting background; the shaded histogram represents the signal function resulting from the fit to the data.

We obtain an estimate of systematic uncertainty on the number of $\pi^0$'s in each $m_{\text{recoil}}(\pi^0)$ interval by repeating the fits to the individual $m(\gamma\gamma)$ spectra with the lineshape parameters corresponding to Fig. 2 varied within their uncertainties. The distribution of the net uncertainty varies as a third order polynomial in $m_{\text{recoil}}(\pi^0)$. We estimate a systematic uncertainty of $\pm 210$ events on the $h_b$ signal yield due to the $\pi^0$-yield extraction procedure by evaluating this function at the fitted $h_b$ mass value.

The dominant systematic uncertainty on the measured
In summary, we have found evidence for the decay $\Upsilon(3S) \to \pi^0 h_b \to \gamma \eta_b$ with a significance of 3.0 standard deviations, including systematic uncertainties. The measured mass value, $m = 9902 \pm 4 \pm 1$ MeV/$c^2$, is consistent with the expectation for the $h_b(1P)$ bottomonium state, the axial vector partner of the $\chi_{bJ}(1P)$ triplet of states. We obtain $B(\Upsilon(3S) \to \pi^0 h_b) \times B(h_b \to \gamma \eta_b) = (3.7 \pm 1.1 \pm 0.7 \text{ (syst.)}) \times 10^{-4}$ (< 5.8 x 10^{-4} at 90% C.L.).

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and
for the substantial dedicated effort from the computing organizations that support BaBar. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MICIN (Spain), STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union), the A. P. Sloan Foundation (USA) and the Binational Science Foundation (USA-Israel).

* Now at Temple University, Philadelphia, Pennsylvania 19122, USA
† Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡ Now at University of South Alabama, Mobile, Alabama 36688, USA
§ Also with Università di Sassari, Sassari, Italy
[12] The MC events are generated using the Jetset7.4 and PYTHIA programs to describe the hadronization process from the Lund string fragmentation model with final-state radiation included. [15].
[15] This quantity is indicative of the collimation of an event topology, with values close to one for jetlike events; the kinematics of a heavy object such as the ηb decaying hadronically result in a more spherical event.
[17] In MC simulations, fits to the individual m(γγ) spectra that make use of a polynomial background function and various combinations of Crystal Ball [19] and/or Gaussian signal functions proved unsatisfactory at the high statistical precision necessary.