

The ground state of bottomonium has finally been found

The first measured hyperfine splitting in the heaviest of all meson families reveals the spin dependence of the force between bottom quarks.

For 10 years the PEP-II electron-positron collider at SLAC has spent most of its time making B mesons in pairs so that particle physicists could study subtle correlations in the decays of those very heavy mesons. They were searching primarily for new physics beyond the field's standard model (see PHYSICS TODAY, May 2001, page 17). But early this year, faced with PEP-II's imminent final shutdown, the BaBar collaboration, which operated the so-called B-factory's detector, decided it would be useful to run the collider in its last few months at several collision energies just below the threshold for making B pairs.

The idea was to take care of some important unfinished business that had eluded PEP-II, its competitors, and its predecessors in the three decades since the discovery of the b (for "bottom") quark, which is five times heavier than the proton. The B mesons are quark-antiquark bound states of the b and one of the four lighter quarks. But before the first B mesons were seen in 1983, b quarks had already revealed themselves in a sequence of the even heavier bottomonium mesons—that is, $b\bar{b}$ bound states (see figure 1). (The top quark, almost 40 times heavier than the b, is too short-lived to form bound states.)

Many other bottomonium mesons have been found since the discovery of the upsilon sequence of figure 1. But like the upsilons, all have had the spins of their two spin-1/2 constituent quarks aligned to form triplet spin-1 configurations. Surely each such triplet state must have a singlet spin-0 hyperfine partner. One could call them, respectively, ortho- and parabottomonium.

Quantum chromodynamics (QCD), the standard theory of strong quark interactions, says that the spin-singlet bottomonium states should be lighter than their triplet partners by a fraction of 1%. But before PEP-II's farewell run, which ended in April, no such state had ever been found. So there was essentially no empirical information about

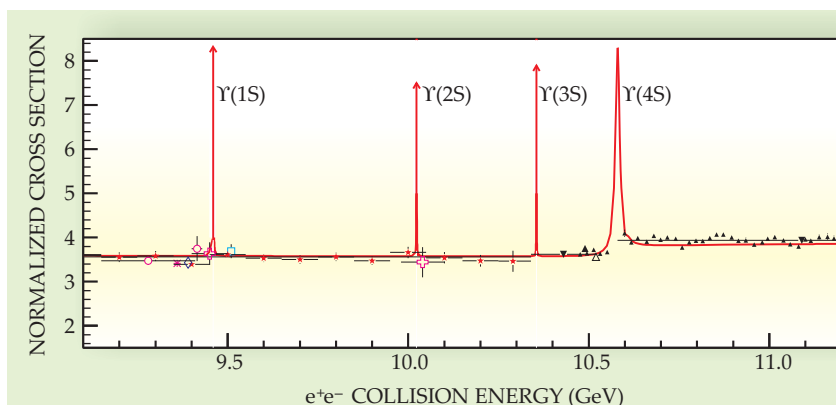


Figure 1. Four prominent peaks in the electron-positron scattering cross section, plotted against collision energy, manifest four Υ bottomonium mesons. They are all spin-1, S-wave bound states of the heavy b quark and its antiquark. None lives longer than 10^{-20} s. The normalized cross section is the ratio of the cross section for creating hadrons to that for creating muon pairs. Because the $\Upsilon(4S)$ is the only one massive enough to decay into pairs of B mesons, it's the only one whose lifetime-broadened intrinsic width is big enough to see here. (Adapted from Particle Data Group, *J. Phys. G: Nucl. Part. Phys.* **33**, 1, 2006.)

the spin dependence of the force between b quarks.

Now the BaBar collaboration, which will continue analyzing its rich trove of data for several more years, has reported the long-awaited discovery of the bottomonium ground state.¹ Labeled η_b , the new spin-singlet meson turns out to be 71 ± 4 MeV lighter than its hyperfine partner $\Upsilon(1S)$. As shown in figure 1, the $\Upsilon(1S)$ with a mass of 9.46 GeV (roughly that of a boron atom), was the first and lightest of the spin-triplet bottomonium states revealed in the late 1970s as resonant peaks in the cross section for e^+e^- scattering.

The measured hyperfine mass splitting between $\Upsilon(1S)$ and η_b is a boon to QCD theorists trying to validate various tricks for extracting usefully precise predictions from the notoriously difficult theory. Partly that's because they seek to confirm that QCD is indeed the correct theory of the strong interactions. But there's a more pressing issue. In the ardent search for new physics beyond the standard model, the experimental breakthrough is generally expected to

come in the observation of delicate weak-interaction phenomena like B-meson decay asymmetries rather than in strong-interaction manifestations like the spectrum of bottomonium states or their decay rates. That's because a whiff of new physics among the strong interactions is likely to be overwhelmed by standard-model phenomena. But even when looking for new physics hiding under the weak interactions, experimenters often have to contend with peripheral strong-interaction effects that muddy the waters. That's especially true for the B decays. Neutralizing such obscuring complications necessitates number-crunching QCD simulations that require simplifying approximations. And the new BaBar result helps to determine how valid those simulations are.

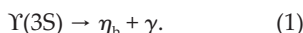
Seeking the ground state

The only bottomonium mesons an e^+e^- collider can make directly are the $\Upsilon(nS)$ states, all of which have the same spin and parity as the photon. The S denotes that the two constituent quarks are in an

S-wave state of zero orbital angular momentum, and n is the principal quantum number of their joint wave function.

Why was it so hard to find the η_b ? Shouldn't the $\Upsilon(1S)$ relax spontaneously to the bottomonium ground state by emitting a photon? Indeed that radiative decay is presumed to happen, but only rarely in the 10^{-20} -second lifetime allotted by competing decay processes in which the b and $\bar{b}$ quarks annihilate each other. In any case, the telltale monochromatic photon signal of such rare decays would be of too low energy (71 MeV, as we now know) to find amidst the debris of the e^+e^- collision.

Therefore, the BaBar collaboration, led by Hassan Jawahery (University of Maryland), spent most of the collider's remaining time running at an e^+e^- center-of-mass collision energy of 10.355 GeV, the mass of the $\Upsilon(3S)$. The idea was to search for the radiative decay



QCD predicted that, at best, the $\Upsilon(3S)$ would decay this way only a few times in a thousand. But when it did, it would produce a monochromatic photon signal near 900 MeV, an energy high enough to give BaBar a fighting chance. And unlike the heavier $\Upsilon(4S)$ whose decays have produced most of BaBar's B-meson-pairs over the decade, the $\Upsilon(3S)$ lies below the mass threshold for making B pairs and thus avoids the impossibly obscuring background they would engender.

The budget axe

Amid a plague of sudden budget cuts last December, the US Department of Energy had decreed that PEP-II be shut down for good in February. But in response to BaBar's proposal to run at the $\Upsilon(3S)$ mass—and also at the $\Upsilon(2S)$ mass—DOE granted PEP-II a two-month reprieve. With the collider working at top form, the reprieve allowed the BaBar collaboration to record 120 million e^+e^- collisions at the $\Upsilon(3S)$ mass. That's 10 times more than all the previous $\Upsilon(3S)$ events accumulated by BaBar, the similar Belle detector at Japan's KEKB collider, and the older CLEO detector at Cornell University's CESR collider. The completion of the final PEP-II run marks the end of accelerator-based particle physics experiments at SLAC after four enormously productive decades (see *PHYSICS TODAY*, May 2005, page 26).

The BaBar detector is a large complex of charged-particle tracking chambers and neutral-particle calorimeters. The problem was to ferret out a modest

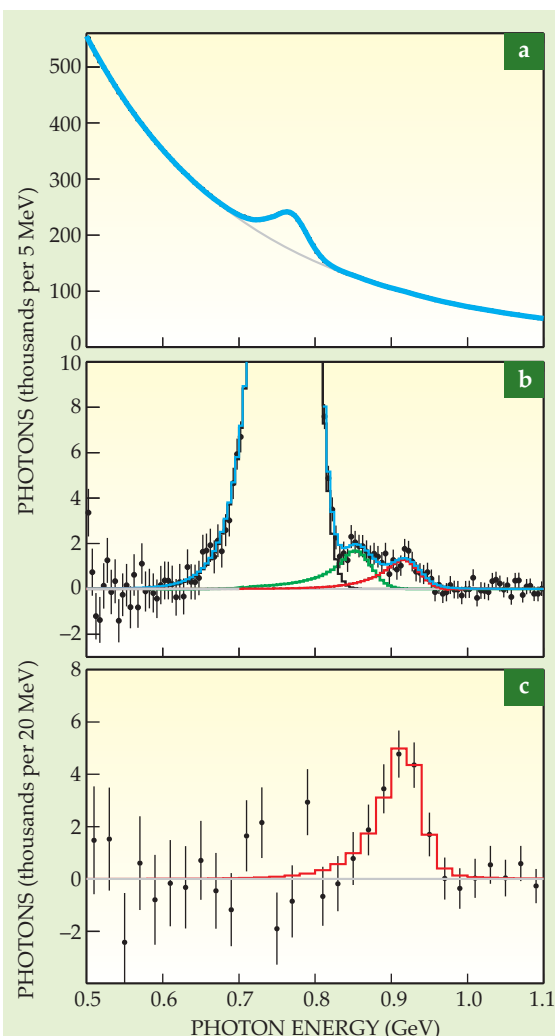


Figure 2. The spectrum of high-energy photons recorded when the PEP-II collider ran at the $\Upsilon(3S)$ mass. Various back-grounds have to be subtracted before the small signal from the $\Upsilon(3S)$ meson's radiative decay to the η_b bottomonium ground state is fully revealed. (a) After all event-selection cuts have been applied, the gross features of the remaining spectrum are a broad peak around 760 MeV, well fitted by the radiative decays of three P -wave daughters of the $\Upsilon(3S)$ and a smooth continuum background. (b) Subtracting the continuum background leaves the large 760-MeV peak plus indications of smaller peaks near 850 and 920 MeV. The two smaller peaks were fitted, respectively, by radiative production of the $\Upsilon(1S)$ (green curve) and the sought-after decay of the $\Upsilon(3S)$ to the η_b (red curve). The branching fraction of that decay and the η_b mass were free parameters in the fits. (c) Subtracting the fitted 760- and 850-MeV peaks from the data in panel (b) leaves the 10-standard-deviation η_b peak, whose size and position measure, respectively, the decay mode's branching fraction and the η_b mass. (Adapted from ref. 1.)

peak somewhere near 900 MeV in the photon spectrum from under an enormous background of high-energy photons from other processes. Judicious culling of events from the total sample was designed to reduce such backgrounds at minimal cost to the η_b signal being sought. For example, BaBar's selection required that in addition to a well-measured high-energy photon a candidate event had to have at least four charged-particle tracks. Whereas the decay of an η_b is expected typically to produce more than half a dozen charged tracks, significant sources of background produce only two charged tracks plus a high-energy photon closely aligned with one of those tracks.

Even for events with many charged tracks, alignment of the photon's direction provided a useful cut. Because the η_b is, by hypothesis, a spinless particle with no preferential decay axis, the di-

rection of its companion photon is essentially uncorrelated with any axis one can construct from its decay products. Because that's generally not true of background events, the analysis discarded all events in which the direction of the high-energy photon was too close to a "thrust axis" constructed from the directions of the other tracks.

Analyzing the data

To avoid unintended biases, all cuts designed to optimize signal-to-noise were predetermined from a 10% subsample of the $\Upsilon(3S)$ data that was subsequently excluded from the final analysis. Then the unknown η_b parameters were determined by fits to the remaining sample.

After all the cuts, the spectrum of high-energy photons was dominated by a smooth continuum background and three sources of spectral peaks, only the smallest of which was the sig-

nal being sought. Figure 2a shows the continuum background plus a broad enhancement peaking near 760 MeV. That enhancement comprises photons from the radiative decays of three well-established P -wave daughters of the $\Upsilon(3S)$ blended into a single peak by Doppler broadening and instrumental energy resolution. Its observed shape and amplitude were useful for calibrating the photon-energy scale and determining search efficiencies.

Happily, that large peak is reasonably well separated from the much smaller η_b peak around 920 MeV, which becomes barely discernible in figure 2b when the continuum background is subtracted from the photon spectrum. More intrusive, however, is another small background peak around 850 MeV, which is attributed to the radiative-production process $e^+ + e^- \rightarrow \Upsilon(1S) + \gamma$.

"Knowing what the magnitude and line shape of the photon signal from this background process should be was crucial to extracting the η_b signal crowding its shoulder," says SLAC physicist Philippe Grenier, a leader of the analysis team. That knowledge let the team subtract off the radiative-production background as well as the larger, more remote 760-MeV enhancement to finally reveal, in figure 2c, the η_b peak standing alone. The energy resolution of the photon calorimeters accounts for its width.

The BaBar team attributes a statistical significance of 10 standard deviations to the η_b discovery peak. Its position yields the mass of the η_b and thus the 71 ± 4 MeV hyperfine splitting between it and the $\Upsilon(1S)$. Estimating that their efficiency for finding photons from reaction 1 was about 37%, the team concluded from the roughly

20 000 photons under the η_b peak that the probability (called the branching fraction) for a $\Upsilon(3S)$ to decay via reaction 1 is about 5×10^{-4} .

Lattice QCD

Because b quarks are so massive, they move relatively slowly inside a bottomonium meson. So there's some hope that theorists trying to reproduce or predict spectroscopic features of the bottomonium family can use nonrelativistic models of the quarks bound in some effective potential to circumvent the daunting complexities of full-blown QCD. Unfortunately, the potential-model predictions of the ground-state hyperfine splitting have ranged from 35 to 100 MeV. But now that BaBar has measured that splitting with an admirable uncertainty of less than 6%, it appears the lattice QCD technique has done better than the potential models.

Lattice QCD calculations, which require prodigious computing resources, approximate the spacetime continuum with closely spaced lattice points. At those points, one simulates the quantum fluctuations of the gluon field that mediates the strong force to predict how quarks and gluons will behave in situations where perturbative approximations are useless (see the article by Carleton DeTar and Steven Gottlieb in *PHYSICS TODAY*, February 2004, page 45).

The most recent major lattice-QCD assault on the bottomonium states was completed three years ago by Cornell theorist Peter Lepage and coworkers.² They predicted a ground-state hyperfine splitting of 61 ± 14 MeV, in good agreement with the BaBar result, albeit with a bigger uncertainty. "Beating down the theoretical error takes enormous time and effort," says Lepage,

"which has to be motivated by shrinking experimental errors." He and his coworkers are now gearing up again to match BaBar's small error.

"It's particularly important to determine how well lattice QCD simulates b quarks," argues Lepage. Their heaviness dictates a more closely spaced lattice, and hence greater computational effort, than what's needed for simulating lighter quarks. That's because the lattice spacing shouldn't exceed the quark's Compton wavelength, which varies inversely with mass.

But it's largely because the B mesons are so heavy that their weak-interaction decays are a favored venue of searches for a breach in the standard model. "If BaBar or Belle eventually claim to have found a small but significant signal of new physics in the B decays," says Lepage, "the claim could easily be dismissed as some strong-interaction complication inadequately treated by lattice QCD—unless we're able to demonstrate how small the lattice QCD errors really are."

Lattice QCD has yet to provide a tight prediction of the branching fraction for the radiative decay of the $\Upsilon(3S)$ to the η_b . But it can more easily predict the ratio of the $\Upsilon(3S)$ and $\Upsilon(2S)$ branching fractions. That's one reason why Jawahery and company ran the collider for almost a month at the $\Upsilon(2S)$ mass. They hope soon to report the measured branching fraction for the radiative decay of that state to the bottomonium ground state.

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References

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Calving icebergs may cause glacial earthquakes in Greenland

Recent local measurements and numerical simulations constrain the possible mechanisms for glacial dynamics that occur on the time scale of minutes.

Most earthquakes follow a simple scaling law: The duration in seconds of slip on the fault is proportional to $10^{M/2}$, where M is the earthquake's moment magnitude, a dimensionless number logarithmically related to the energy release. A typical $M = 5$ earthquake lasts 2 seconds; an $M = 7$ one, 20 seconds. The short duration gives rise to the efficiently radiated high-frequency seismic waves most often used to detect and locate earthquakes around the world.

But earthquakes exist with durations—from tens to thousands of seconds, say—much longer than the scaling law would suggest. And because they radiate more of their energy as long-period waves, the events often go undetected. In 2003 Göran Ekström, a seismologist at Columbia University, was looking for such oddballs. He systematically mined three years of archival data from the global seismographic network, which monitors about

200 seismometers distributed worldwide. His algorithm filtered the data in the long-period band between 35 and 150 seconds and checked whether a coherent-energy signal could be traced to any of some 5000 different locations on Earth.

Surprisingly, the grid search uncovered hundreds of never-before-cataloged earthquakes. And dozens, whose magnitudes ranged between 4.6 and 5.1, came from glaciated regions,