PROCEEDINGS OF SCIENCE

Observation of $\Upsilon(4S) \to \eta'\Upsilon(1S)$ and $\Upsilon(2S) \to \gamma\eta_b(1S)$ at Belle

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Bottomonium is the bound state of a bottom quark and its anti-quark counterpart. This talk presents two recent first observations from the Belle experiment related to hadronic and radiative decays in the bottomonium system. The first is the observation of $\Upsilon(4S) \to \eta'\Upsilon(1S)$, and the second is the decay of $\Upsilon(2S) \to \gamma\eta_b(1S)$. The purpose of this talk is to present details of both analyses.

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1. Introduction

Quarkonium is the bound state of a heavy quark and its anti-quark counterpart. Phenomenological models, nonrelativistic QCD, and lattice calculations predict a large spectrum of particles whose properties (*e.g.* mass, width, spin, production and decay mechanisms, etc.) can be verified in experiment. There have been many recent discoveries in this field, including several first observations of long-predicted quarkonia, but also many apparent "XYZ" states that cannot be explained within the quarkonium framework [1]. The analyses presented in this talk focus on conventional bottomonium decays.

The Belle Experiment operated at the asymmetric KEKB e^+e^- collider in Tsukuba, Japan from 1999 to 2010, collecting approximately 1.0 ab^{-1} of data at various center-of-mass energies to produce various bottomonium resonances. It has made many significant contributions to the study of quarkonium, including discovery of the $\eta_b(2S)$ and $h_b(1P, 2P)$ $b\bar{b}$ states, and exotic $Z_b^{\pm}(10610/50)$ four-quark particles.

2. $\Upsilon(4S) \to \eta'\Upsilon(1S)$ [2]

2.1 Motivation

While the majority of $\Upsilon(4S)$ decays are to $B\bar{B}$ pairs [3], a small fraction have been observed to inclusive $\Upsilon(1S)$ final states. Recent experimental measurements of hadronic η bottomonium decays have shown unexpectedly enhanced rates [4, 5, 6] compared to theoretical predictions.

Transitions involving excited η' have yet to be observed. In the charm sector, there have been null searches for $\psi(4160)$ and $Y(4260)$ decaying to the equivalent $\eta' J/\psi$ [7] by CLEO, while energy scan results from BESIII indicate evidence for such final state decays from e^+e^- center-of-mass energies of 4.226 and 4.258 GeV [8]. Theoretical calculations for $\psi(4160)$ decays via η' predict a branching ratio approximately 6% of that via η [9]. By analogy this leads to an expected branching fraction for $\Upsilon(4S) \to \eta'\Upsilon(1S)$ on the order of 10^{-5}.

2.2 Analysis

The Belle analysis uses 496 fb^{-1} of e^+e^- collision data taken at the $\Upsilon(4S)$ resonance, equivalent of $(538 \pm 8) \times 10^6$ $\Upsilon(4S)$ decays. The $\Upsilon(1S)$ is reconstructed decaying to $\mu^+\mu^-$, and two η' final states are considered: $\eta' \to \rho^0\gamma$ and $\eta' \to \pi^+\pi^-\eta$. The data are skimmed to require at least two tracks with high momentum, and one of the two muons is required to be identified as such by Belle particle identification procedures. An invariant mass selection of $9.3 < M(\mu\mu) < 9.6$ GeV/c^2 is applied. To remove continuum background events, a kinematic boundary requirement is applied of $p(\mu^+\mu^-)_{CM} - \frac{1}{2}\frac{(s-m(\mu^+\mu^-)^2)}{\sqrt{s}} < 0$, where p and m are the momentum and mass of the $\mu^+\mu^-$ system, and s is the center-of-mass energy of the collisions. For the $\eta' \to \rho\gamma$ final state, to remove backgrounds from $\Upsilon(2S, 3S)$ decays produced with initial state radiation, output from a boosted decision tree (BDT) is created with input from $\Delta M_{\pi\pi} = M(\mu\mu\pi\pi) - M(\mu\mu)$ and $M(\mu\mu\pi\pi\gamma)$ variables from Monte Carlo simulation studies. Events with BDT output > 0.15 are retained. For this final state, a cut is also applied on the cosine of the angle between the two pions in the center-of-mass frame, $|\cos\theta(\pi\pi)_{CM}| < 0.9$.

The data are fit in the variable $\Delta M_{\eta'} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$. Signal events are extracted using a Gaussian-like fit function defined as $\exp\{-\frac{(x-\mu)^2}{2\sigma^2_{L,R}+\alpha_{L,R}(x-\mu)^2}\}$, where μ represents the peak position, and $\sigma_{L,R}$ and $\alpha_{L,R}$ are parameters that vary on either side of the mean. Background events are fit with a broad Gaussian function for $\rho^0\gamma$, and a straight line for $\pi^+\pi^-\eta$.

2.3 Results

We find 22 ± 7 (5.0 ± 2.3) signal events in the $\rho^0\gamma$ $(\pi^+\pi^-\eta)$ decay mode, corresponding to a significance of $4.2\sigma (4.1\sigma)$. Uncertainties are predominantly statistical, with a total systematic uncertainty of $7.6\% (3.5\%)$, with the largest contributions from lineshape modeling and secondary branching fractions. A simultaneous fit for the two final states finds a branching fraction of $\mathscr{B}(\Upsilon(4S) \to \eta'\Upsilon(1S)) = (3.43 \pm 0.88 \pm 0.21) \times 10^{-5}$, where the uncertainties are respectively statistical and systematic, for a significance of 5.7σ. This represents the first observation of this decay mode. The ratio of this branching fraction compared to transitions to $\Upsilon(1S)$ via η and $\pi^+\pi^-$ is 0.20 ± 0.06 and 0.42 ± 0.11, respectively. These results may be indiciative of contributions from additional light quark degrees of freedom in the initial $\Upsilon(4S)$ state [10].

3. $\Upsilon(4S) \to \gamma\eta_b(1S)$ [11]

3.1 Motivation

Properties of the bottomonium ground state, $\eta_b(1S)$ have long been predicted by many different theoretical models [12]. The branching fraction for suppressed M1 radiative $\Upsilon(2S) \to \gamma\eta_b(1S)$ decays have predictions in the range of $(2-20) \times 10^{-4}$. BaBar reported evidence for this decay mode with 3.7σ significance, finding $(3.9 \pm 1.5) \times 10^{-4}$ and measuring $m_{\eta_b(1S)} = 9394.2 \pm 4.9$ MeV/c^2. Other mass measurements derived from radiative Υ decays are consistent with this value, while those from $h_b(nP) \to \gamma\eta_b 1S$ transitions (where $n = 1$ or 2), are nearly 3σ higher.

3.2 Analysis

The Belle analysis examines the inclusive photon energy spectrum from $(157.8 \pm 3.6) \times 10^6$ $\Upsilon(2S)$ decays. Five peaking structures are expected above a very large smooth background: $\Upsilon(2S) \to \gamma\eta_b(1S)$ signal events, initial state radiation photons from direct $e^+e^- \to \Upsilon(1S)$ production, and three overlapping Doppler-broadened peaks from $\chi_{b0,1,2}(1P) \to \gamma\Upsilon(1S)$ decays.

Photon candidates are required to be reconstructed in the Belle barrel electromagnetic calorimeter. The ratio of energy deposited in the innermost 9 crystals compared to the 25 centered on the cluster must be greater than 0.925. To reject photons from π^0 decay, each photon candidate is paired with all others with energy $E_\gamma > 60$ MeV in the event, and if their invariant mass falls within 15 MeV of the nominal π^0 mass, they are rejected. To reject continuum background, the absolute value of the cosine of the angle between the photon and the thrust axis of the rest of the event is required to be less than 0.9.

After application of the selection criteria, the efficiency for the peaking structures ranges from $26-32\%$, and the lineshape resolution varies from $8-12$ MeV. The data are fit with the peaking structures modeled by variants on the Crystal Ball function [13], while the background is fit with an exponential with a fifth-order polynomial.

3.3 Results

We find $\chi_b(1P)$ branching fractions and transition energies consitent with past CLEO [14] and BaBar [15] measurements. The initial state radiation transition energy and yield are consistent with theoretical predictions [16]. We measure an $\Upsilon(2S) \to \gamma\eta_b(1S)$ branching fraction of $(6.1^{+0.6+0.9}_{-0.7-0.5}) \times 10^{-4}$, and $m_{\eta_b(1S)} = 9394.8^{+2.7+4.5}_{-3.1-2.7}$ MeV. The branching fraction is consistent with recent lattice calculations [17], while the mass is consistent with all previous experimental measurements. The largest systematic uncertainties on the mass measurement come from the signal lineshape parameterization (not considered by previous experimental measurements), and calibration of the energy scale, which was verified using several control modes ($\chi_{b1,2}(1P)$ transitions, $D^{*0} \to D^0\gamma$, $\eta \to \gamma\gamma$, etc.). The significance of this $\eta_b(1S)$ measurement is greater than 7σ, making it the first observation of this decay mode.

4. Summary

The Belle experiment continues to make important contributions to the study of the bottomonium system. This talk presented two first observations: the hadronic transition $\Upsilon(4S) \to \eta'\Upsilon(1S)$ and the radiative transition $\Upsilon(2S) \to \gamma\eta_b(1S)$. Studies of bottomonium will continue at Belle, and soon at the upgraded next generation flavor factory experiment, Belle II.

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