PROCEEDINGS OF SCIENCE

Decays and spectroscopy at $\Upsilon(1S,2S)$ at Belle

Matthew Barrett[*]
University of Hawai'i at Mānoa
On behalf of the Belle collaboration
E-mail: mattb@phys.hawaii.edu

Recent results from the Belle collaboration involving $\Upsilon(1S)$ and $\Upsilon(2S)$ meson decays are reported. Four sets of analyses are described: the observation of the decay $\Upsilon(2S) \to \Upsilon(1S)\eta$, and the search for $\Upsilon(2S) \to \Upsilon(1S)\pi^0$; the decays $\Upsilon(1S)/\Upsilon(2S) \to$ light hadrons; the search for double charmonium decays from $\chi_{bJ}(1P)$; and new preliminary results from the search for bottomonium exclusive decays to hyperon-antihyperon pairs.

36th International Conference on High Energy Physics
4-11 July 2012
Melbourne, Australia

PoS(ICHEP2012)341

---

[*] Speaker.

1. Introduction

The Belle detector [1] collected over 1ab^{-1} of data, including 25fb^{-1} running at an energy corresponding to the mass of the $\Upsilon(2S)$ resonance, and 6fb^{-1} at the energy of the $\Upsilon(1S)$. These are the world's largest datasets at these resonances, and represent the creation of 102 million $\Upsilon(1S)$, and 158 million $\Upsilon(2S)$ particles. For the $\Upsilon(2S)$ dataset, 32% ($\sim$ 50.5 million) of the $\Upsilon(2S)$ mesons decay to states including an $\Upsilon(1S)$, including 19% ($\sim$ 30 million) which are $\pi^+\pi^-$ tagged $\Upsilon(2S)$ to $\Upsilon(1S)$ transitions.

This document describes four analyses of $\Upsilon(1S)$ and $\Upsilon(2S)$ decays — each of which uses the full available dataset(s).

2. The decay $\Upsilon(2S) \to \Upsilon(1S)\eta$.

The decay $\Upsilon(nS) \to \Upsilon(mS)\pi^+\pi^-$ is an E1E1 transition, and does not require a spin flip. Conversely, the decays $\Upsilon(nS) \to \Upsilon(mS)\eta$, $\Upsilon(mS)\pi^0$ are E1M2 transitions, which do require a spin flip. The QCD multipole expansion [2] predicts that there should be a suppression of the mode containing an η meson with respect to the mode containing two charged pions. Results from BaBar and CLEO do not agree with theory predictions. BaBar measures a branching fraction [3] of $B(\Upsilon(4S) \to \Upsilon(1S)\eta) = (1.96 \pm 0.11) \times 10^{-4}$, which is 2.5 times larger than for the mode with two charged pions. For the mode $\Upsilon(3S) \to \Upsilon(1S)\eta$ theory predicts a branching fraction of (1–10)$\times 10^{-4}$ and BaBar sets a limit [4] of $B(\Upsilon(3S) \to \Upsilon(1S)\eta) < 1.0 \times 10^{-4}$. The theory prediction for $B(\Upsilon(2S) \to \Upsilon(1S)\eta)$ is (4–8)$\times 10^{-4}$; CLEO measures $B(\Upsilon(2S) \to \Upsilon(1S)\eta) = 2.1 \times 10^{-4}$ [5], and BaBar reports a value of $B(\Upsilon(2S) \to \Upsilon(1S)\eta) = 2.39 \times 10^{-4}$ [4]; both measurements are lower than expectations.

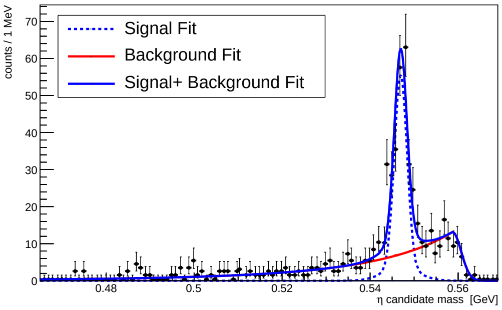

Figure 1: The mass distribution of η candidates reconstructed in the analysis of $\Upsilon(2S) \to \Upsilon(1S)\eta$, showing the signal, background and combined fits.

Belle searches for the decay $\Upsilon(2S) \to \Upsilon(1S)\eta$, by reconstructing the $\Upsilon(1S)$ via the decay $\Upsilon(1S) \to l^+l^-$ ($l = e, \mu$). The η meson is reconstructed in one of two modes, either $\eta \to \gamma\gamma$ or $\eta \to \pi^+\pi^-\pi^0$. Figure 1 shows the η candidate mass distribution, with the dashed line showing the signal fit, and the solid line showing the combined fit. The fit gives a result of $B(\Upsilon(2S) \to \Upsilon(1S)\eta) = (3.41 \pm 0.28 \pm 0.35) \times 10^{-4}$, where the first uncertainty is statistical and the second is systematic. This is higher than previous measurements (the current value from the Particle Data Group (PDG) is $B(\Upsilon(2S) \to \Upsilon(1S)\eta) = (2.34 \pm 0.31) \times 10^{-4}$ [6]), but consistent with theoretical predictions.

In addition, there is a search for the decay $\Upsilon(2S) \to \Upsilon(1S)\pi^0$. This mode is further suppressed by isospin with respect to the mode with the η meson. The π^0 meson is reconstructed via its decay to two photons. No significant signal is observed, and an upper limit of $B(\Upsilon(2S) \to \Upsilon(1S)\pi^0) < 0.43 \times 10^{-4}$ is calculated at 90% confidence level (CL). This is more restrictive than the previous best limit from CLEO of $B(\Upsilon(2S) \to \Upsilon(1S)\pi^0) < 1.8 \times 10^{-4}$ [5].

3. $\Upsilon(1S)/\Upsilon(2S) \to$ light hadrons.

In the charmonium sector there is an estimate of the ratio of branching fractions:

$$Q_\psi = \frac{B_{\psi(2S)\to\text{hadrons}}}{B_{J/\psi\to\text{hadrons}}} = \frac{B_{\psi(2S)\to e^+e^-}}{B_{J/\psi\to e^+e^-}} \sim 12\%, \tag{3.1}$$

which is known as the "12% rule". This "rule" is not followed in some Vector-Pseudoscalar (VP) and Vector-Tensor (VT) decays, for example $\psi(2S), J/\psi \to \rho\pi$.

For bottomonium there is an equivalent prediction:

$$Q_\Upsilon = \frac{B_{\Upsilon(2S)\to\text{hadrons}}}{B_{\Upsilon(1S)\to\text{hadrons}}} = \frac{B_{\Upsilon(2S)\to e^+e^-}}{B_{\Upsilon(1S)\to e^+e^-}} = 0.77 \pm 0.07, \tag{3.2}$$

this prediction is expected to hold better for the higher mass Upsilon mesons than for charmonium mesons.

Belle studied the the decays of $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons to light hadrons in ten channels (for each):

- 3 three-body modes: ϕK^+K^-, $\omega\pi^+\pi^-$, $K^{*0}K^-\pi^+$;
- 4 VT modes: $\phi f_2'$, ωf_2, ρa_2, $K^{*0}K_2^{*0}$;
- 3 Axial-vector-Pseudoscalar (AP) modes: $K_1(1270)^+K^-$, $K_1(1400)K^-$, $b_1(1235)^+\pi^-$.

The signal yield is calculated by fitting mass distributions of the reconstructed particles. Table 1 shows the fitting results for all ten channels [7]. There is a significant signal observed in five of the channels (for at least one of the two Upsilon mesons). This includes all three of the three body modes; these results are the first observation of exclusive three-body hadronic annihilations of $\Upsilon(1S)/\Upsilon(2S)$. The values of Q_Υ are in agreement with equation 3.2, though for the $\omega\pi^+\pi^-$ mode a deviation of 2.6 standard deviations (σ) is observed. However a significant signal is observed for only the $\Upsilon(1S)$ meson decay for this mode.

4. Search for double charmonium decays from $\chi_{bJ}(1P)$.

Measurements of production of double charmonium states has produced results that have been higher than predictions from leading order nonrelativistic quantum chromodynamics (NRQCD). A number of models were proposed to explain the discrepancy. Measurements of production of double charmonium states from $\chi_{bJ}(1P)$ states would provide additional information for discriminating between and refinement of these models.

Table 1: A table showing the results of the search for the decays $\Upsilon(1S,2S) \to$ light hadrons [7]. N^{sig} is the number of signal events obtained from a fit, N^{UP}_{sig} is the upper limit on this quantity for cases where N^{sig} is not statistically significant, Σ is the statistical significance from the fit, expressed in terms of standard deviations, B is the calculated branching fraction for each channel, and B^{UP} is the upper limit on the branching fraction. Q_Υ is the ratio defined in equation 3.2, and Q^{UP}_Υ is the upper limit on Q_Υ for cases where one or both of the $\Upsilon(1S,2S)$ modes do not have a significant branching fraction. For quantities where two uncertainties are shown the first is statistical, and the second systematic.

Channel	$\Upsilon(1S)$					$\Upsilon(2S)$						
	N^{sig}	N^{UP}_{sig}	Σ	B	B^{UP}	N^{sig}	N^{UP}_{sig}	Σ	B	B^{UP}	Q_Υ	Q^{UP}_Υ
ϕK^+K^-	56.3 ± 8.7		8.6	$2.36\pm0.37\pm0.29$		58 ± 12		6.5	$1.58\pm0.33\pm0.18$		$0.67\pm0.18\pm0.11$	
$\omega\pi^+\pi^-$	63.6 ± 9.5		8.5	$4.46\pm0.67\pm0.72$		29 ± 12	51	2.5	$1.32\pm0.54\pm0.45$	2.58	$0.30\pm0.13\pm0.11$	0.55
$K^{*0}K^-\pi^+$	173 ± 20		11	$4.42\pm0.50\pm0.58$		135 ± 23		6.4	$2.32\pm0.40\pm0.54$		$0.52\pm0.11\pm0.14$	
$\phi f'_2$	6.9 ± 3.9	15	2.1	$0.64\pm0.37\pm0.14$	1.63	8.3 ± 6.0	18	1.6	$0.50\pm0.36\pm0.19$	1.33	$0.77\pm0.70\pm0.33$	2.54
ωf_2	5.2 ± 4.0	13	1.5	$0.57\pm0.44\pm0.13$	1.79	-0.4 ± 3.3	6.1		$-0.03\pm0.24\pm0.01$	0.57	$-0.06\pm0.42\pm0.02$	1.22
ρa_2	29 ± 11	49	2.7	$1.15\pm0.47\pm0.18$	2.24	10 ± 11	30	0.9	$0.27\pm0.28\pm0.14$	0.88	$0.23\pm0.26\pm0.12$	0.82
$K^{*0}K^{*0}_2$	42.2 ± 9.5		5.4	$3.02\pm0.68\pm0.34$		32 ± 11		3.3	$1.53\pm0.52\pm0.19$		$0.52\pm0.21\pm0.07$	
$K_1(1270)^+K^-$	3.7 ± 4.9	13	0.8	$0.54\pm0.72\pm0.21$	2.41	11.0 ± 4.4	26	1.2	$1.06\pm0.42\pm0.32$	3.22	$1.96\pm2.71\pm0.84$	4.73
$K_1(1400)K^-$	23.8 ± 8.2		3.3	$1.02\pm0.35\pm0.22$		9.2 ± 8.2	24	0.5	$0.26\pm0.23\pm0.09$	0.83	$0.26\pm0.25\pm0.10$	0.77
$b_1(1235)^+\pi^-$	14.4 ± 6.9	28	2.4	$0.47\pm0.22\pm0.13$	1.25	1.2 ± 3.5	13	0.2	$0.02\pm0.07\pm0.01$	0.40	$0.05\pm0.16\pm0.03$	0.35

For $\chi_{bJ}(1P) \to J/\psi J/\psi$ NRQCD [8] predicts a branching fraction of 10^{-5} for $J = 0,2$ or 10^{-11} for $J = 1$. Predictions also exist from perturbative QCD [9] and using the light cone formalism [10] (Table 2), which are of similar magnitude to each other, but significantly higher than the NRQCD predictions.

Table 2: Predictions of the branching fractions for χ_{bJ} decays to double charmonium states using the light cone formalism [10].

	$J = 0$	$J = 2$
$\chi_{bJ}(1P) \to J/\psi J/\psi$	9.6×10^{-5}	1.1×10^{-3}
$\chi_{bJ}(1P) \to J/\psi\psi'$	1.6×10^{-4}	1.6×10^{-3}
$\chi_{bJ}(1P) \to \psi'\psi'$	6.6×10^{-5}	5.9×10^{-4}

Belle searches for 9 different decay modes: $\chi_{bJ}(1P) \to J/\psi J/\psi$, $\chi_{bJ}(1P) \to J/\psi\psi'$, $\chi_{bJ}(1P) \to \psi'\psi'$ for each of $J = 0,1,2$. This search is carried out via radiative decays of the $\Upsilon(2S)$, i.e. $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$. One of the charmonium particles in the decay is fully reconstructed, and it is required that the missing mass in the event is consistent with the mass of the second charmonium particle.

There is no significant signal observed in any of the channels [11], and upper limits are placed on each of the channels; these are summarised in Table 3. These upper limits are much lower than the central values predicted by pQCD and by light cone formalism. The limits are consistent with NRQCD calculations.

5. Bottomonium exclusive decays to hyperon-antihyperon pairs.

Belle searched for the decays of bottomonium states ($\Upsilon(1S)$, $\Upsilon(2S)$, and χ_{bJ}) to hyperon-antihyperon pairs ($\Lambda\bar{\Lambda}$, $\Xi\bar{\Xi}$, or $\Omega\bar{\Omega}$), with up to two light mesons (either no additional particles, an η meson, a single π^0 meson, or a $\pi^+\pi^-$ pair). Some of these decay modes have been observed for charmonium states with branching fractions of $10^{-4} - 10^{-5}$.

Table 3: Summary of the upper limits at 90% confidence level for χ_{bJ} decays to double charmonium modes [11]. In the table n^{up} is the upper limit on the number of signal events, ε is the sum of efficiencies from different modes with J/ψ and ψ' branching fractions and trigger efficiency included, σ_{sys} is the total systematic error, and B_R is the upper limit on the branching fraction.

Channel	n^{up}	$\varepsilon(\%)$	$\sigma_{sys}(\%)$	B_R
$\chi_{b0} \to J/\psi J/\psi$	21	5.8	16	7.1×10^{-5}
$\chi_{b1} \to J/\psi J/\psi$	13	6.3	30	2.7×10^{-5}
$\chi_{b2} \to J/\psi J/\psi$	22	5.9	27	4.5×10^{-5}
$\chi_{b0} \to J/\psi \psi'$	20	3.4	17	1.2×10^{-4}
$\chi_{b1} \to J/\psi \psi'$	5.8	3.8	15	1.7×10^{-5}
$\chi_{b2} \to J/\psi \psi'$	17	3.5	16	4.9×10^{-5}
$\chi_{b0} \to \psi' \psi'$	3.0	2.1	20	3.1×10^{-5}
$\chi_{b1} \to \psi' \psi'$	12	2.2	17	6.2×10^{-5}
$\chi_{b2} \to \psi' \psi'$	3.3	2.1	12	1.6×10^{-5}

Events are fully reconstructed; the $\Upsilon(1S)$ and χ_{bJ} decays are reconstructed via $\Upsilon(2S) \to \Upsilon(1S) + X$ and $\Upsilon(2S) \to \gamma\chi_{bJ}$ respectively. To increase efficiency the $\Upsilon(1S)$ and χ_{bJ} are not tagged. Events are then selected that contain exactly one hyperon and one anti-hyperon. Signal yields are extracted from the mass distribution, fitting each mass distribution for peaks corresponding to the masses of the $\Upsilon(2S)$, $\Upsilon(1S)$, and χ_{bJ} mesons. The mass distributions are shown in Figure 2. The $\Xi\bar{\Xi}$ and $\Omega\bar{\Omega}$ samples are expected to be almost free of background events in the signal fitting region.

Table 4: Preliminary upper limits on the branching fractions of each channel used in the search for bottomonium decays to hyperon-antihyperon pairs.

	Upper limit $/10^{-6}$		
Channel	$S = \Lambda$	$S = \Xi$	$S = \Omega$
$\Upsilon(2S) \to S\bar{S}$	0.17	0.89	1.8
$\Upsilon(2S) \to S\bar{S}\pi^0$	0.79	2.3	6.6
$\Upsilon(2S) \to S\bar{S}\eta$	0.82	2.8	7.4
$\Upsilon(2S) \to S\bar{S}\pi^+\pi^-$	0.30	0.61	2.0
$\Upsilon(1S) \to S\bar{S}$	0.59	1.8	6.7
$\Upsilon(1S) \to S\bar{S}\pi^0$	3.7	7.8	23
$\Upsilon(1S) \to S\bar{S}\eta$	3.7	12	24
$\Upsilon(1S) \to S\bar{S}\pi^+\pi^-$	4.6	4.8	9.6
$\chi_{bJ}(1P) \to S\bar{S}$	0.59	1.8	6.7
$\chi_{bJ}(1P) \to S\bar{S}\pi^+\pi^-$	4.6	4.8	9.6

No significant signal is seen in any of the channels, and upper limits are placed on all channels, using a Feldman–Cousins approach for channels with no background, and a Frequentist approach with backgrounds modelled as exponential distributions for channels with backgrounds. These upper limits are given in Table 4.

References

[1] A. Abashian *et al*. (Belle Collaboration). *Nucl. Instr. Meth.*, **A479**:117–232, 2002.

[2] Y.-P. Kuang. *Front. Phys. China*, **1**:19–37, 2006.

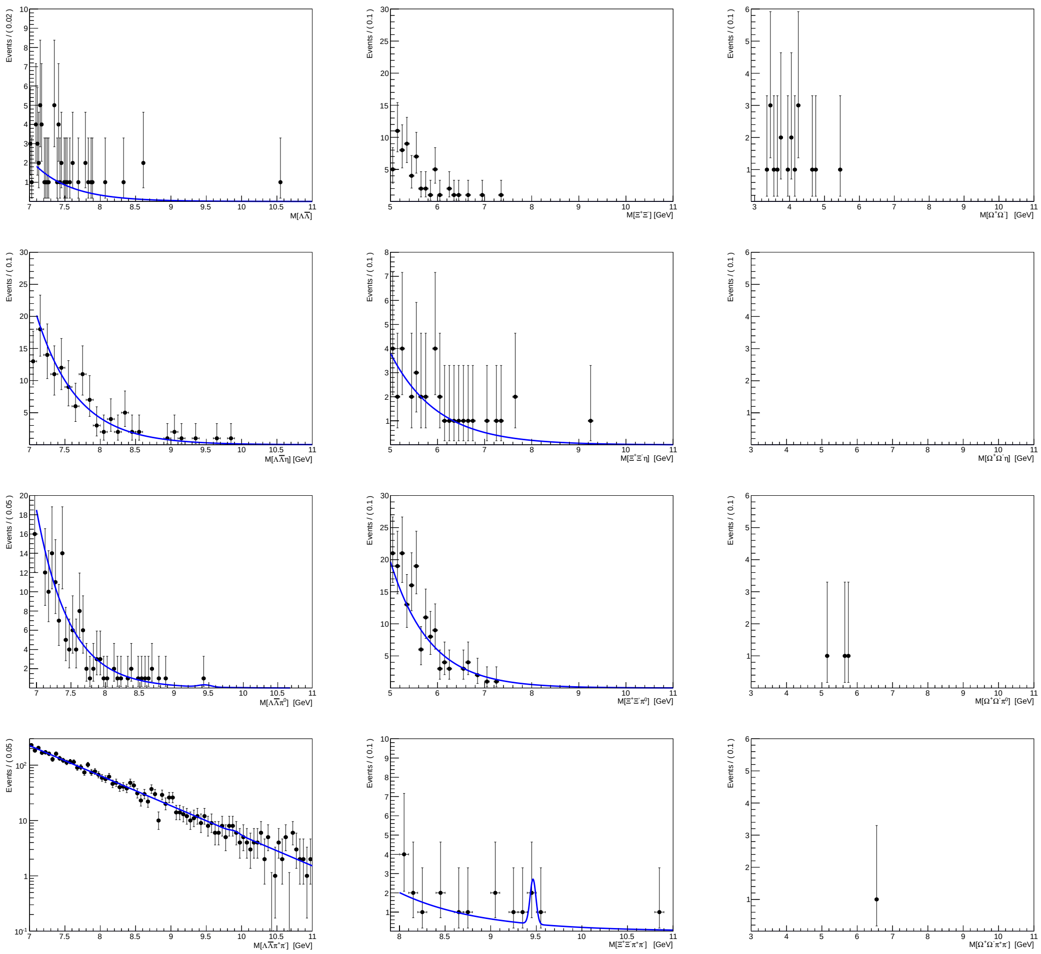

Figure 2: Preliminary mass distributions for each of the final states. Top row: $\Lambda\bar{\Lambda}$(left), $\Xi\bar{\Xi}$(centre), $\Omega\bar{\Omega}$(right); second row: $\Lambda\bar{\Lambda}\eta$(left), $\Xi\bar{\Xi}\eta$(centre), $\Omega\bar{\Omega}\eta$(right); third row: $\Lambda\bar{\Lambda}\pi^0$(left), $\Xi\bar{\Xi}\pi^0$(centre), $\Omega\bar{\Omega}\pi^0$(right); bottom row: $\Lambda\bar{\Lambda}\pi^+\pi^-$(left), $\Xi\bar{\Xi}\pi^+\pi^-$(centre), $\Omega\bar{\Omega}\pi^+\pi^-$(right).

[3] B. Aubert *et al*. (BaBar collaboration). *Phys. Rev. D*, **78**:112002, 2008.

[4] J. P. Lees *et al*. (BaBar collaboration). *Phys. Rev. D*, **84**:092003, 2011.

[5] Q. He *et al*. (CLEO collaboration). *Phys. Rev. Lett.*, **101**:192001, 2008.

[6] J. Beringer *et al*. (Particle Data Group). *Phys. Rev. D*, **86**:010001, 2012.

[7] C. P. Shen *et al*. (The Belle Collaboration). *Phys. Rev. D*, **86**:031102(R), 2012.

[8] Hairong Dong Juan Zhang and Feng Feng. *Phys. Rev. D*, **84**:094031, 2011.

[9] A. K. Likhoded V. V. Braguta and A. V. Luchinsky. *Phys. Rev. D*, **72**:094018, 2005.

[10] A. K. Likhoded V. V. Braguta and A. V. Luchinsky. *Phys. Rev. D*, **80**:094008, 2009.

[11] C. P. Shen *et al*. (The Belle Collaboration). *Phys. Rev. D*, **85**:071102(R), 2012.