Bottomonium Results from $\text{BaBar}$ and $\text{BELLE}$

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After nine years of operation the $\text{BaBar}$ experiment at the B factory PEPII (Stanford Linear Accelerator Center) stopped data taking in April 2008. The last three month of data taking were devoted to $e^+e^-$ collisions at center of mass energies of the $\Upsilon(2S)$, $\Upsilon(3S)$ and to an energy scan above the $\Upsilon(4S)$. Besides the observation of the bottomonium ground state $\eta_b$, the center of mass energy dependent $e^+e^-$ production cross section was measured in the energy range from 10.54 to 11.20 GeV. $\text{BELLE}$ observed an enhancement in the production cross section for $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ in an energy scan from 10.83 to 11.02 GeV.

1 Introduction

The bound states of $b\bar{b}$, the bottomonium states, are the heaviest and most compact bound states of quarks and anti quarks in nature. They were first discovered as spin triplet states called $\Upsilon$ by the $\text{E288}$ collaboration at Fermilab in 1977 in $p$ scattering on Cu and Pb targets studying muon pairs in a regime of invariant masses larger than 5 GeV. Thirty years after the discovery of these $b\bar{b}$ triplet states, still no evidence for the lowest energy spin singlet state, the pseudo scalar $\eta_b$, was found.

Spectroscopic measurements of fine and hyperfine structure splittings of hadronic and radiative transitions in the bottomonium system allow to test calculations of NRQCD, QCDME and lattice QCD. In particular, the hyperfine mass splitting between the singlet and triplet states yields information about the spin-spin interactions. Of the recent topics in bottomonium physics, $\text{BaBar}$’s discovery of the $\eta_b$ and the measurement of the hyperfine splitting are discussed. Results of an inclusive $b\bar{b}$ cross section measurement of a precision energy scan above the $\Upsilon(4S)$ are presented. These results are compared to an exclusive cross section measurement of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ by $\text{BELLE}$ in a scan on the $\Upsilon(5S)$ resonance.

2 Discovery of the $\eta_b$ Meson

The large BABAR dataset on $\Upsilon(3S)/(2S)$ of 120 million/100 million events allows to search for the rare radiative $M1$ transitions from the triplet states $\Upsilon(3S)$ and $\Upsilon(2S)$ to the $\eta_b$.

The strategy is to search in the inclusive photon spectrum for the decay $\Upsilon(3S) \rightarrow \gamma \eta_b$ in the center of mass frame of the $\Upsilon(3S)$. Besides the signal photons at an energy of about 900 MeV, we expect large backgrounds of non-peaking and peaking nature. Continuum $q\bar{q}$ events, $\Upsilon(3S)$ cascade decays and $\Upsilon(3S) \rightarrow \gamma gg$ events contribute to the non-peaking background. There are two contributions to the peaking background: i) the decay chain from $\Upsilon(3S)$ to the triplet $\chi_{bJ}^+$, $\chi_{bJ}^0$...

*The 3 states of the $\chi_{bJ}(2S)$ decaying to $\Upsilon(1S)$ appear as one peak at about 760 MeV due to energy resolution
which then decays to $\Upsilon(1S)$, ii) initial state radiation (ISR) with a photon of such a radiated energy ($E_\gamma \approx 860$ MeV) that the remaining virtual photon matches the $\Upsilon(1S)$.

Knowing all sources entering the inclusive photon spectrum, for each contribution a probability density function (PDF) is determined. A binned maximum likelihood fit in the photon energy range from 500 to 1100 MeV allows to extract the $\eta_b$ signal. About 10% of the data are used to improve the PDF determination, the event selection and the background suppression. This data are discarded in the final analysis. The shape of the photon distribution ($E_\gamma = s - m^2 / 2\sqrt{s}$) of the decay to $\eta_b$ is determined from MC as a convolution of a Crystal Ball and a Breit-Wigner function. The width of the Breit-Wigner function is fixed to 10 MeV and variations are considered as systematic errors. For the non-peaking background component an exponential Ansatz is used; the starting parameters are determined from the side bands. The $\chi_b J(2S)$ decays are parametrized as 3 Crystal Ball functions. Their width is fixed and is for all 3 lines the same. The relative peak positions are taken from PDG. The relative yields are also fixed. In the final fit the yield of the contribution from ISR ($e^+ e^- \rightarrow \gamma_{ISR} \Upsilon(1S)$) is fixed and taken from the extrapolated yield of the $\Upsilon(4S)$ off-peak data to the $\Upsilon(3S)$ on-peak sample taking the luminosity, the reconstruction efficiency and the cross section into account.

A maximum likelihood fit of the four components to the data sample with an integrated luminosity of 25.6 $fb^{-1}$ (109 million $\Upsilon(3S)$ events) is performed. Figure 1a shows the inclusive photon spectrum and the PDFs of the fit result as colored lines after subtracting the non-peaking background. The $\chi_b J(2S)$ contribution is indicated in light blue, in green the contribution from initial state radiation. The $\eta_b$ peak in magenta is clearly visible. Subtracting the $\chi_b$ and ISR contributions leads to the $\eta_b$ signal shown in the upper right part of Figure 1a. The photon energy is measured to be \( \langle E_\gamma \rangle = 921.2^{+2.1}_{-2.8} \pm 2.4 \) MeV with a significance of 10$\sigma$.

In addition to the $\eta_b$ search in $\Upsilon(3S)$ data, BABAR performed a similar analysis using 92 Million $\Upsilon(2S)$ events\footnote{The $\eta_b$ discovery is confirmed in this channel with a signal significance of 3.5$\sigma$. Both values of the $\eta_b$ mass agree very well. The combined mass of the $\eta_b$ is measured to be $M_{\eta_b} = 9390.4 \pm 3.1$ MeV/c$^2$, which is in good agreement with unquenched lattice QCD calculations.} The $\eta_b$ signal shown in the upper right part of Figure 1a. The photon energy is measured to be \( \langle E_\gamma \rangle = 921.2^{+2.1}_{-2.8} \pm 2.4 \) MeV with a significance of 10$\sigma$.

The ratio of the branching fraction measurements for $\Upsilon(3S) \rightarrow \eta_b \gamma$ and $\Upsilon(2S) \rightarrow \eta_b \gamma$ is $R_B = B(\Upsilon(2S) \rightarrow \gamma \eta_b) / B(\Upsilon(3S) \rightarrow \gamma \eta_b) = 0.89^{+0.25+0.12}_{-0.23-0.16}$. According to Godfrey and Rosner,\footnote{This is consistent with the assumption of radiative M1 transitions and Doppler broadening.} this is compatible with the assumption of radiative M1 transitions.
Recently, non-baryonic charmonium states which do not behave like standard \( c\bar{c} \) states were discovered. The question arises, if similar exotic states with \( J^{PC} = 1^{--} \) appear in the bottomonium energy regime. Scaling the \( \Upsilon \) states (4260, 4350, 4660) from the charmonium to the bottomonium regime, the interesting energy range is above \( \Upsilon(4S) \) and below 11.2 GeV. \( \text{BaBar} \) performed a scan in the center of mass energy from 10.54 to 11.2 GeV in 5 MeV steps with 25 \( pb^{-1} \) of recorded data per point. This is about 4 times finer with a 30 times larger amount of data than the last scan done 25 years ago at CESR [18]. Including 8 additional points of irregular spacing on \( \Upsilon(6S) \), the total amount of data corresponds to an integrated luminosity of 3.9 \( fb^{-1} \).

\( \text{BaBar} \) follows an inclusive approach to search for new states with \( b \) quark content measuring the inclusive hadronic cross section as the ratio \( R_b(s) = \sigma_{bb(\gamma)}(s)/\sigma_{\mu\mu}^0(s) \) at different center of mass energies [14]. Here, \( \sigma_{bb(\gamma)}(s) \) is the total cross section of \( e^+e^- \rightarrow b\bar{b}(\gamma) \) including the \( b\bar{b} \) states produced in initial state radiation below the open beauty threshold and \( \sigma_{\mu\mu}^0(s) \) is the lowest order cross section of \( e^+e^- \rightarrow \mu^+\mu^- \). The region above the \( \Upsilon(4S) \) is explored with unprecedented details as shown in Figure 2 by the measurement of \( R_b \) as function of the center of mass energy. The errors are of statistical and uncorrelated systematic nature. The dotted lines indicate the different \( B \) meson production thresholds. The large statistics per energy point and the small energy steps reveal structures which seem to correspond to threshold openings. The \( \Upsilon(5S) \) and \( \Upsilon(6S) \) candidates are probably not pure resonance structures as predicted within the coupled channel model in 1984 by Törnquist [10]. It handles the coupling between the quarkonia and the continuum. Coupled channel effects play a significant role in accounting for the energy spacing of the \( nS \) level. All resonances contribute by interference with the dominant resonance. Therefore, an interpretation of the measured structures is very difficult. The bumps in the region from 10.6 to 10.75 GeV are not due to resonances, but appear due to threshold openings of the \( B^*\bar{B} \) and \( B^*\bar{B}^* \) and the node structure in the overlap integrals. Above \( \Upsilon(6S) \) a plateau is clearly visible.

In order to determine the parameters for the \( \Upsilon(5S) \) and \( \Upsilon(6S) \) candidates, the following simplified model is fit to the data in the energy range from 10.8 to 11.2 GeV: \( \sigma = |A_{nr}|^2 + |B_r + A_5 e^{i\phi_5} BW(M_{5S}, \Gamma_{5S}) + A_6 e^{i\phi_6} BW(M_{6S}, \Gamma_{6S})|^2, BW(M, \Gamma) \) is a relativistic Breit-Wigner resonance. The values obtained \( M(\Upsilon(5S)) = 10876 \pm 2 \text{ MeV}/c^2, \Gamma(\Upsilon(5S)) = 43 \pm 4 \text{ MeV}/c^2 \) and \( M(\Upsilon(6S)) = 10960 \pm 2 \text{ MeV}/c^2, \Gamma(\Upsilon(6S)) = 37 \pm 3 \text{ MeV}/c^2 \) differ significantly from the PDG values \( M(\Upsilon(5S)) = 10865 \pm 8 \text{ MeV}/c^2, \Gamma(\Upsilon(5S)) = 110 \pm 13 \text{ MeV}/c^2 \) and \( M(\Upsilon(6S)) = 11019 \pm 8 \text{ MeV}/c^2, \Gamma(\Upsilon(6S)) = 79 \pm 16 \text{ MeV}/c^2 \). The result of the fit is superimposed in Figure 2 (right). The number of states and their energy dependence is a priori unknown. Therefore, a calculation within a proper coupled channel approach would certainly yield different results.

In contrast to \( \text{BaBar} \), \( \text{BELLE} \) followed an exclusive approach measuring the energy dependence of the cross section of \( e^+e^- \rightarrow \Upsilon(nS) \pi^+\pi^- \rightarrow \mu^+\mu^- \pi^+\pi^- \) (\( n = 1, 2, 3 \)) in an energy scan within the \( \Upsilon(5S) \) region [11]. Data of six energy points from 10.83 to 11.02 GeV corre-
Figure 3: The center of mass energy dependent cross sections for $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^- \ (n = 1, 2, 3)$ processes. a) The results of a fit with a common mean and width of an S-wave Breit-Wigner model are shown as curves. b) The results of a fit with the PDG $\Upsilon(5S)$ and $\Upsilon(6S)$ parameters is superimposed.

The large BaBar datasets on $\Upsilon(2S)/\Upsilon(3S)$ resulted in the discovery of the lowest energy spin singlet state of the bottomonium system $\eta_b$ in $\Upsilon(3S) \rightarrow \eta_b\gamma$ decays. The $\eta_b$ mass was measured to be $M_{\eta_b} = 9390.4 \pm 3.1 \text{ MeV}/c^2$ with a hyperfine splitting $\Delta M_{\Upsilon(1S) - \eta_b} = 69.9 \pm 3.1 \text{ MeV}/c^2$.

These measurements were complemented by an inclusive hadronic cross section measurement above $\Upsilon(4S)$ from 10.54 to 11.2 GeV which revealed structures with unprecedented detail. BaBar extracted from the fit of a simplified model parameters for $\Upsilon(5S)$ and $\Upsilon(6S)$ which indicate a smaller width than the PDG values. This is supported by a cross section measurement from BELLE of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$ in the $\Upsilon(5S)$ region of 10.83 to 11.02 GeV. 

4 Summary

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