PROCEEDINGS OF SCIENCE

New bottomonium spectroscopy and transitions

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Recent results in bottomonium spectroscopy are reviewed. Topics include the observation of $\Upsilon(nS) \rightarrow \eta\Upsilon(1S)$ transitions, energy scans above the $\Upsilon(4S)$ resonance by the BABAR and Belle experiments, and the recent observation of the η_b by the BABAR experiment.

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†A footnote may follow.

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1. Introduction

Until recently, the CLEO experiment had the largest data bottomonium data samples, with 22×10^6 $\Upsilon(1S)$, 9×10^6 $\Upsilon(2S)$ and 6×10^6 $\Upsilon(3S)$ decays. Much larger samples have now been acquired by BABAR with 99×10^6 $\Upsilon(2S)$ and 122×10^6 $\Upsilon(3S)$ events and Belle, with 100×10^6 $\Upsilon(1S)$ and 11×10^6 $\Upsilon(3S)$ events. In the past year, the BABAR and Belle experiments have also performed scans above the $\Upsilon(4S)$ resonance. These new datasets have already provided many new results.

2. Hadronic transitions

Hadronic transitions between bottomonium states are often described within the QCD multipole expansion (QCDME). If the radius a of a source is smaller than the wavelength of the radiated gluon field, $\lambda\sim1/k$, one can expand the gluon field in powers of ak. Since the typical radius of a bottomonium state is of order 10^{-1}fm the QCDME is expected to work well for low-lying states. In the charmonium system the ratio $\Gamma(\psi(2S)\to\eta J/\psi)/\Gamma(\psi(2S)\to\pi^+\pi^-J/\Psi)$ as well as the $\pi\pi$ mass spectrum in $\psi(2S)\to\pi^+\pi^-\psi$ transitions are predicted correctly. In the bottomonium system there are many more allowed transitions below open threshold to test the QCDME.

2.1 $\Upsilon(nS)\to(\pi^0,\eta)\Upsilon(mS)$ transitions

In the QCDME single π^0 and η transitions are suppressed relative to the corresponding dipion transition as the single pseudoscalar transition proceeds via a higher order in the multipole expansion, an $E1M2$ or $M1M1$ transition versus an $E1E1$ transition for the dipion transition.

CLEO has observed for the first time a process involving a b-quark spin flip, supressed due to the large b-quark mass, the transition $\Upsilon(2S)\to\eta\Upsilon(1S)$, with a significance of 5.3 standard deviations [1]. The branching fraction for this transition is $\mathscr{B}[\Upsilon(2S)\to\eta\Upsilon(1S)]=(2.1^{+0.7}_{-0.6}\pm0.3)\times10^{-4}$. Related transitions were not observed and upper limits at 90% confidence level for related processes, in units of 10^{-4}, are $\mathscr{B}[\Upsilon(2S)\to\pi^0\Upsilon(1S)]<1.8$, $\mathscr{B}[\Upsilon(3S)\to\eta\Upsilon(1S)]<1.8$, $\mathscr{B}[\Upsilon(3S)\to\pi^0\Upsilon(1S)]<0.7$, and $\mathscr{B}[\Upsilon(3S)\to\pi^0\Upsilon(2S)]<5.1$. The data are presented in fig. 1.

BABAR has searched for η transitions between $\Upsilon(mS)$ $(m=4,3,2)$ and $\Upsilon(nS)$ $(n=2,1)$ resonances in an analysis based on 383.2×10^6 $\Upsilon(4S)$ decays [2]. The $\Upsilon(4S)$ is produced directly whereas lower Υ initial states are produced via ISR. BABAR has provided the first observation of $\Upsilon(4S)\to\eta\Upsilon(1S)$ decay with a branching fraction $\mathscr{B}[\Upsilon(4S)\to\eta\Upsilon(1S)]=(1.96\pm0.06\pm0.09)\times10^{-4}$ resulting in the ratio of partial widths $\Gamma(\Upsilon(4S)\to\eta\Upsilon(1S))/\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))=2.41\pm0.40\pm0.12$. This is larger than the value of $10^{-2}-10^{-3}$ [3] predicted by the QCDME. The data are presented in fig. 1.

2.2 $\Upsilon(nS)\to\pi^+\pi^-\Upsilon(mS)$ transitions

BABAR also present new measurements of the ratios $\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))=1.16\pm0.16\pm0.14$ and $\Gamma(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S))/\Gamma(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S))=0.577\pm0.026\pm0.060$ [2]. While the di-pion mass spectrum in the $4S\to1S$ transition is in excellent agreement with QCDME predictions, there is a low mass structure in $4S\to2S$ transitions which is not yet understood.

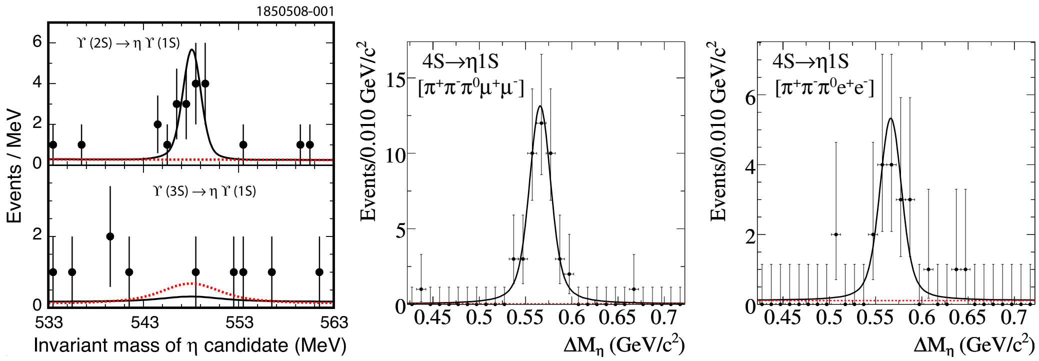

Figure 1: Invariant mass distribution of η candidates in kinematically allowed $\Upsilon(3S) \to \eta\Upsilon(nS)$ transitions from CLEO (left). Fits to $\Delta M_\eta = M_{3\pi\ell\ell} - M_{\ell\ell} - m_{3\pi}$ distribution for $\Upsilon(4S) \to \eta\Upsilon(1S)$ candidates with $\Upsilon(1S) \to \mu^+\mu^-$ (center) and $\Upsilon(1S) \to e^+e^-$ (right) in BABAR $\Upsilon(4S)$ data.

The Belle experiment has observed unusually large di-pion transition rates of the $\Upsilon(10860)$, with the transition rate $\Upsilon(10860) \to \pi^+\pi^-\Upsilon(1S)$ of 0.59 MeV, a factor of ~ 1000 larger than the rates of $\Upsilon(nS) \to \pi^+\pi^-\Upsilon(1S)$ of 60, 9, and 19 MeV for $n = 2,3$, and 4, respectively [4].

3. Scans above the $\Upsilon(4S)$

Recent observations of exotic charmonium states, as well as the Belle results for anomalous $\Upsilon(10680) \to \pi^+\pi^-\Upsilon(nS)$ production, have motivated searches for similar states in the bottomonium system.

Belle has performed a scan of the energy region $\sqrt{s} = 10.83$ GeV to $\sqrt{s} = 11.02$ GeV [5]. They observe an enhancement in the $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$, $n = 1,2,3$ cross section which is not consistent with the shape of the $\Upsilon(10860)$ and $\Upsilon(11020)$ hadronic cross section. The results are shown in fig. 2.

BABAR has performed a scan of the energy region 10.54 GeV to 11.20 GeV [6], also shown in fig. 2. The interpretation of the results is strongly dependent upon the position of threshold openings [7, 8].

4. Observation of the η_b at BABAR

Though the bottomonium system was discovered over thirty years ago, the spin-singlet states have remained elusive. These include the ground state of the bottomonium system, the η_b. Earlier this year the BABAR experiment accumulated $30 fb^{-1}$ on the $\Upsilon(3S)$ resonance, where the η_b may be seen in the hindered $M1$ radiative decay $\Upsilon(3S) \to \gamma\eta_b$.

The yield of the signal peak is $19200 \pm 2000 \pm 2100$ events, with a statistical significance, including systematic errors, of 10σ. The signal peak, after subtracting all backgrounds, is shown in fig. 3. The measured branching fraction of $(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$ rules out many theoretical predictions of $M1$ transition rates.

Though neither the spin nor the parity has been measured, the agreement with the theoretical predictions for the η_b mass, and expected M1 transition rate, leads to an interpretation of the peak

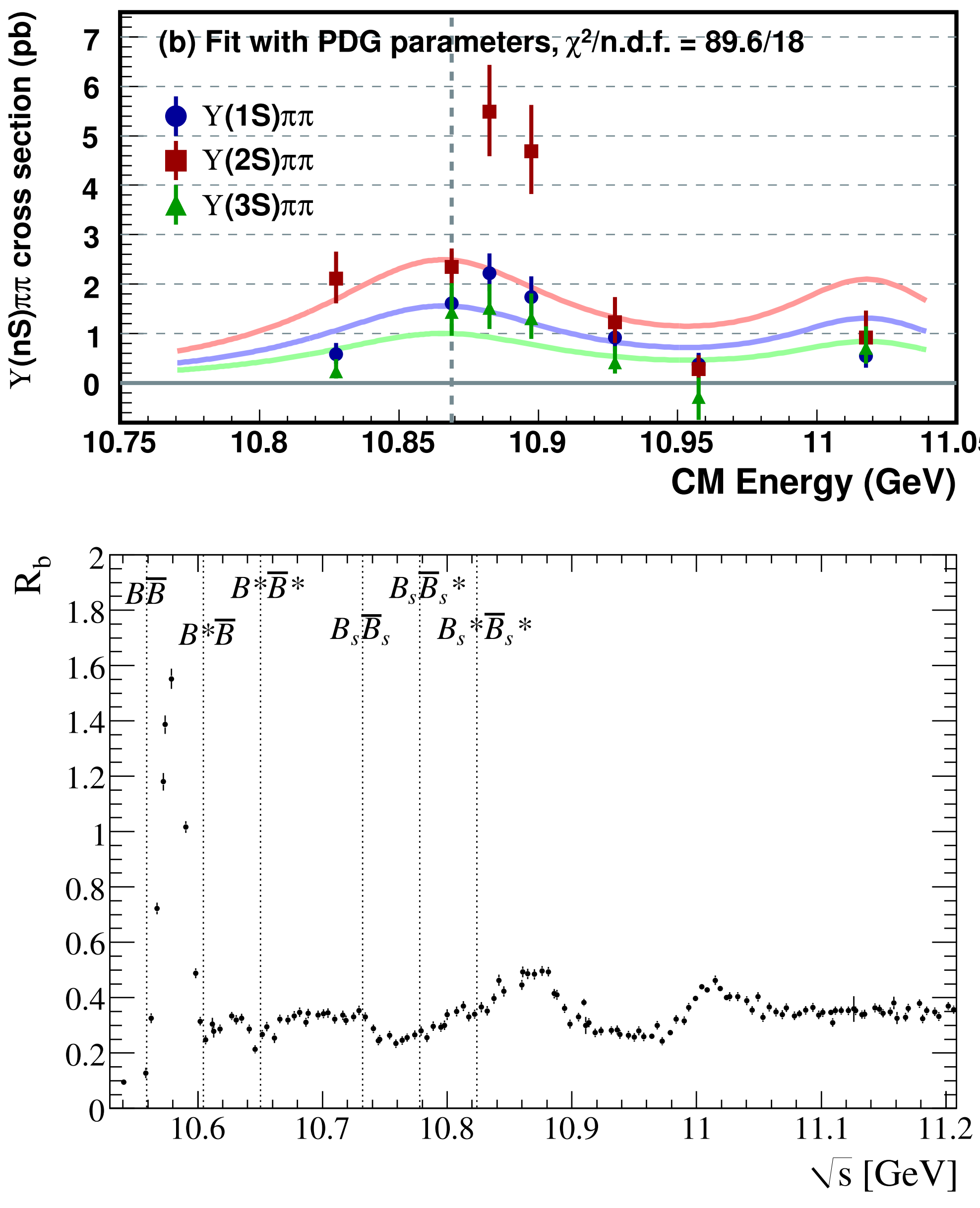

Figure 2: (Top) Production cross section of $e^+e^- \to \pi^+\pi^-\Upsilon(nS), n = 1,2,3$ from the Belle experiment. The fit curves describe two non-interfering Breit-Wigner pdfs representing the $\Upsilon(10860)$ and $\Upsilon(11020)$ states on top of a flat background. (Bottom) BABAR scan of the energy region 10.54 GeV to 11.20 GeV. The vertical dotted lines mark threshold openings.

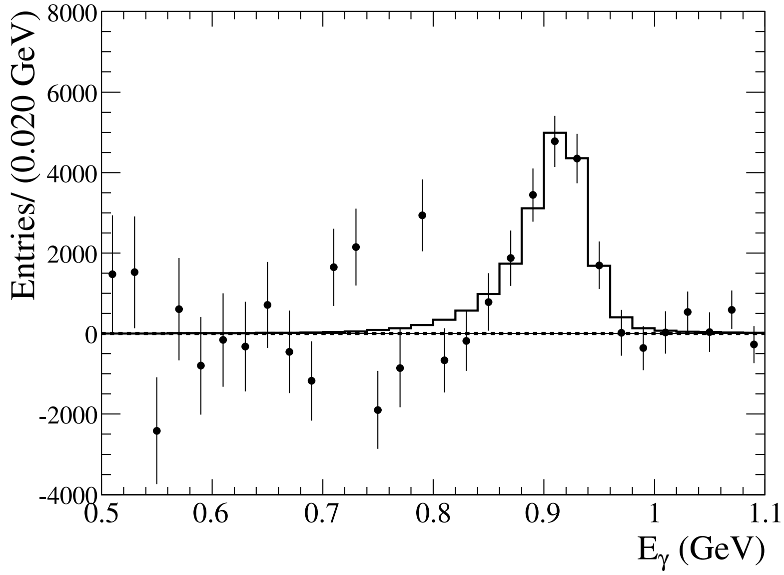

Figure 3: Signal peak for decay $\Upsilon(3S) \rightarrow \gamma\eta_b$ after subtracting all backgrounds, from the BABAR experiment.

as being due to the η_b. Under this interpretation, the mass of the η_b is $9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV$/c^2$, corresponding to a hyperfine splitting between the η_b and $\Upsilon(1S)$ of $71.4^{+2.3}_{-3.1} \pm 2.7MeV/c^2$, ruling out many QCD and potential model predictions.

5. Conclusion

Recent new data has provided a great deal of new information regarding bottomonium spectroscopy and transitions. The recently acquired data has not yet been fully analyzed. With the much larger datasets currently available, observation of the $\eta_b(2S)$ and the h_b should be possible, as well as a confirmation of $\Upsilon(1D)$ states and precision measurements of electic dipole transition rates.

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