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Recent results from BaBar

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We present recent results on bottomonium spectroscopy, rare neutral D mesons decays, and semi-leptonic Bs mesons decays. They are based on datasets collected at the Υ(2S), Υ(3S), and Υ(4S) resonances and slightly below and above (up to twice the Λb mass) by the BaBar detector at the PEP-II storage rings at SLAC from year 2000 to 2008. All the results presented here are preliminary.

I. BOTTOMIUM SPECTROSCOPY

A. Introduction

The bottomonium spectroscopy below the B ¯ B mass threshold is somewhat richer than in the case of charmonium state [1, 2], below the D ¯ D mass threshold. The measurement of the bottomonium mass states and of the branching ratios (B) are important tests of the heavy qq potential models and set constraints on lattice QCD, as well as on theories such as pNRQCD. Hadronic transitions probe non-perturbative QCD. While bottomonium states with quantum numbers L = 0, 1 and S = 1 have been observed and abundantly studied since 1977, not all the predicted states have been observed. In particular no spin singlet are presently observed until 2008 [3]. The first D-wave state Υ(1DJ=2) has only been observed in 2004 by CLEO, in the transition γγΥ(1S) and latter on in 2010 by BaBar, in the channel π⁺π⁻Υ(1S) [4].

At the end of its operation in 2008, the BaBar experiment collected large datasets of approximately 120M Υ(3S) and 100M Υ(2S) events, creating renewed possibilities for probes on bottomonium system. We present herein a study of the Υ(2S), Υ(3S), and Υ(4S) resonances and slightly below and above (up to twice the Λb mass) by the BaBar detector at the PEP-II storage rings at SLAC from year 2000 to 2008. All the results presented here are preliminary.

A search of ηb(1S) and ηb(2S) quarkonia is performed in radiative transitions using an experimental technique employing converted γ rays in the Υ(2S) and Υ(3S) decays. The h0(1P) state is searched in the Υ(3S) → h0(1P)π⁺π⁻ decays, and an evidence of signal is seen in the channel with a neutral pion. A search of the rare FCNC D⁰ → γγ decay is presented and the channel D⁰ → π⁰π⁰ is accurately measured.

Finally, we present a study of the semi-leptonic branching ratio of the Bs mesons and of the f⁺ fraction, the production of Υ(2S) mesons. It is based on the very last BaBar dataset collected in 2008 and corresponding to an energy scan above the Υ(4S) resonances performed at PEP-II.

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seen. It is consistent with previous works by CLEO and CUSB (1992) (see Refs. in [5]) and our measurements are more precise.

In the “medium” \(\Upsilon(3S)\) region we observe the transitions \(\Upsilon(3S) \to \gamma \chi_{b0,2}(1P)\) with more than 7 and 15 statistical standard deviations, while the \(\Upsilon(3S) \to \gamma \chi_{b1}(1P)\) is not seen. This work is in agreement with recent measurements performed by CLEO [7]. An upper limit \(B(\Upsilon(3S) \to \gamma \eta_b(2S)) < 1.9 \times 10^{-3}\) is set at 90% C.L., for a scan of the resonance in the narrow range: \(335 < E_\gamma^* < 375\) MeV.

In the “high” \(\Upsilon(3S)\) region we observe the transitions \(\chi_{b1,2}(2P) \to \gamma \Upsilon(1S)\) with a much better accuracy than CLEO and CUSB, and confirm an absence of observation of the \(\chi_{b0}(2P) \to \gamma \Upsilon(1S)\). For the \(\eta_b(1S)\) state a 2.9 statistical standard deviation signal is seen (respectively 2.7 when including systematic uncertainties that are dominated by width assumption for the signal). The fitted mass of the quarkonium state is \((9403.6 \pm 2.8 \pm 0.9)\) MeV/c\(^2\) and is inconsistent with the PDG average by about 3\(\sigma\) deviations [2]. The measured \(B(\Upsilon(3S) \to \gamma \eta_b(1S)) = (5.9 \pm 1.6\) \(\pm 1.4\) \(\times 10^{-4}\) is however consistent with previous measurements [3].

Finally, for the \(\Upsilon(2S)\) data spectrum one observes the transitions \(\chi_{b1,2}(1P) \to \gamma \Upsilon(1S)\) with a much better accuracy than CLEO and CUSB, and confirms an absence of observation of the \(\chi_{b0}(1P) \to \gamma \Upsilon(1S)\). For the \(\eta_b(1S)\) state a non significant 1.7 statistical standard deviation signal when including systematic uncertainties is obtained (2.5\(\sigma\) for statistics only). The fitted mass of the quarkonium state is nevertheless fairly consistent with the PDG average [2]. One sets the upper limit: \(B(\Upsilon(2S) \to \gamma \eta_b(1S)) < 0.22\%\) at 90% of C.L.

The results of that analysis [5] are the best \(B(\chi_{b0}(nP) \to \gamma \Upsilon(1S, 2S))\) available measurements and in good agreement with theory predictions [8]. We have the most accurate measurements of the transitions \(\Upsilon(3S) \to \gamma \chi_{b0,2}(1P)\) and we don’t observe the \(\chi_{b1}(1P)\). This is inconsistent with any theory prediction but this is in good agreement with CLEO [7]. Unfortunately very few concluding informations are derived for the \(\eta_b(1S, 2S)\) states as initially hoped.
C. Search for \( \Upsilon(3S) \to \pi^0 h_b(1P) \) and \( \pi^+\pi^- h_b(1P) \) transitions

The \( h_b(1P) \) bottomonium state is the axial vector partner of the three \( P \) -wave \( \chi_{bJ}(1P) \) states and its mass is expected to be at the center of gravity of their masses: 
\[
\frac{m_{h_b(1P)}}{\Sigma_J((2J+1)\times m_{\chi_{bJ}(1P)})/\Sigma_J(2J+1)} = (9900 \pm 0(3)) \text{ MeV}/c^2.
\]

The predicted production mechanisms in \( \Upsilon(3S) \) decays are \( B(\Upsilon(3S) \to \pi^0 h_b(1P)) \sim 10^{-3} \) and \( B(\Upsilon(3S) \to \pi^+ \pi^- h_b(1P)) \sim 10^{-5} \sim 10^{-3} \). Such predictions lead to a relative ratio of branching ratios of the 2 decay modes \( (\pi^0/\pi^+\pi^-) \) ranging from 5 to 20%\textsuperscript{[9]}. The \( \Upsilon(3S) \to \gamma h_b(1P) \) decay is forbidden by C-Parity.

The expected \( h_b(1P) \) decay width is less than 1 \( \text{MeV} \). The particle decays to 3 gluons (\( \sim 57\% \)) or to 2 gluons plus a photon (\( \sim 2\% \)), and for 40 - 50% of the time, to \( \gamma h_b(1P) \). The latter mode offers an experimental signature that helps to reduce the background and that can be compared to the technique that was employed by CLEO in 2005 and later on by BES in 2010 to observe the charmonium state \( h_J \), in the decay \( \psi(2S) \to \pi^0 h_J(\gamma\eta) \). More recently CLEO-c\textsuperscript{[10]} measured the decay \( e^+ e^- \to \pi^+ \pi^- h_b(1P) \).

The existing for the branching ratios are:
\[
B(\Upsilon(3S) \to \pi^0 h_b(1P)) \leq 1.8 \times 10^{-3} \quad \text{and} \quad B(\Upsilon(3S) \to \pi^0 h_b(1P)) \leq 2.7 \times 10^{-3} \text{ at 90\% C.L.} \textsuperscript{[2]}
\]

At this conference R. Mizuk\textsuperscript{[11]}, for the BELLE collaboration, has presented the first observation of the \( h_b(1P) \) and \( h_b(1P) \) states in \( \Upsilon(5S) \to \pi^+\pi^- h_b(1P, 2P) \) transitions.

We perform the search in the 2 channels \( \Upsilon(3S) \to \pi^0 h_b(1P) \textsuperscript{[12]} \) and \( \Upsilon(3S) \to \pi^+\pi^- h_b(1P) \textsuperscript{[13]} \).

The \( \Upsilon(3S) \to \pi^0 h_b(1P) \) channel is reconstructed by requiring a photon with an energy \( E_\gamma \) consistent with the transition \( h_b(1P) \to \gamma h_b(1P) \textsuperscript{(540, 540)} \text{MeV} \). Additional selection criteria are applied. They are based on the number of tracks, event shape, and we veto photons matching \( \pi^0 \). The global signal efficiency is about 16\%. The number of signal event is extracted from fits to the distribution of the mass recoiling against the pion system in the \( \Upsilon(3S) \) rest frame and in a mass region near the predicted \( h_b(1P) \) mass (9.9 \( \text{GeV}/c^2 \)). The recoil mass window comprises 90 bins of 3 \( \text{MeV}/c^2 \) width each. Very precise fits to photon pairs are performed and account for accurate effects from re-weighted Monte Carlo simulation to data (the signal region is excluded in the procedure). The average reduced \( \chi^2 \) of the fits presented in Fig. 2 (left) is 0.98 \pm 0.03.

The fit to the recoil mass spectrum yields 9145 \pm 2804 \pm 1082 signal events. This is an evidence for the signal at the level of 3.0 standard deviations and this number includes all the sources of uncertainties (statistical and systematic). The systematic uncertainties are dominated by the background and signal line shape models and the \( m(\gamma\gamma) \) fits. The above signal significance is slightly higher (3.2\sigma) when the systematic uncertainties contributions are omitted. The mass of the \( h_b(1P) \) signal is (9902 \pm 4 \pm 1) \text{ MeV}/c^2 and is fully compatible with an expected value as the centre of gravity of the \( \chi_{bJ}(1P) \) states.

When assuming \( B(h_b(1P) \to \gamma\gamma ) = (45 \pm 5\%) \), we measure \( B(\Upsilon(3S) \to \pi^0 h_b(1P)) = (3.7 \pm 1.1 \pm 0.4) \times 10^{-4} \). We also set the upper limit to be 5.8 \times 10^{-4} at 90\% C.L. It is fully consistent with the prediction by Voloshin\textsuperscript{[9]} and coherent the previous limits.

The \( \Upsilon(3S) \to \pi^+\pi^- h_b(1P) \) channel is reconstructed by requiring a pair of positively-charged track as the dipion pair. Additional criteria are applied. They are based on the event energy and shape, the number of tracks, and we also veto mainly \( K_S^0 \to \pi^+\pi^- \) decays and we reduce also the less worrying baryon decay \( \Lambda \to p\pi^- \) and converted \( \gamma \) to a \( e^+e^- \) pair. The global signal efficiency is about 42\%. Here also a search of a signal peak near 9.9 \( \text{GeV}/c^2 \) is performed by fitting the recoil mass against the dipion system. The signal resolution is expected to be of the order of 9\( \text{MeV}/c^2 \).

The fit of the subtracted combinatorial background spectrum is displayed in Fig. 2 (right). A 1D \( \chi^2 \) fit is performed to extract the signal and it comprises 7 components: the \( h_b(1P) \) signal, the \( \Upsilon(3S) \to \pi^+\pi^- \) transition at the \( \Upsilon(2S) \) mass, the \( \Upsilon(2S) \to \pi^+\pi^- \) contribution slightly below 9.8 \( \text{GeV}/c^2 \), the \( \chi_{bJ}(2P) \to \pi^+\pi^- h_b(1P) \), the remaining \( K_S^0 \to \pi^+\pi^- \) pollution, and the non-peaking background (including ISR \( e^+e^- \)). No signal is seen. The fit yields a negative number of signal events: \( -1106 \pm 2432 \) (statistical uncertainty only is included here). This leads to the upper limit:
\[
B(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) < 1.2 \times 10^{-4} \text{ at 90\% C.L.}
\]

The maximum significance over the scanned range is 2 standard deviations at most. The systematic uncertainties are dominated by the decay knowledge in the simulation for the charmless mesons and by the continuum model and residual \( K_S^0 \) and ISR backgrounds.

We also extract the branching ratios of the transitions \( \Upsilon(3S) \to X[\chi_{bJ}(2P) \to \pi^+\pi^- \chi_{bJ}(1P)] \), where \( J = J' \) and are equal to 1 or 2. We measure: \( B(J = J' = 1 \text{ or 2}) = (1(1.56 \pm 0.07 \pm 0.12) \times 10^{-3} \) or \( 0.64 \pm 0.05 \pm 0.08) \times 10^{-3} \). And we improve the PDG\textsuperscript{[2]} accuracy for the \( B[\Upsilon(3S) \to \pi^+\pi^- \Upsilon(2S)] \) and \( B[\Upsilon(3S) \to X(\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S))] \) decays. We measure respectively: \( (3.00 \pm 0.02 \pm 0.14)\% \) and \( (1.78 \pm 0.02 \pm 0.11)\% \).

Finally it is possible to estimate the ratio of branching ratios \( B(\Upsilon(3S) \to \pi^0 h_b(1P)) \) over \( B(\Upsilon(3S) \to \pi^+\pi^- h_b(1P)) \) from the above measurements. It is higher that 3.7 - 5.8 and so far consistent with predictions from theory\textsuperscript{[9]}.

II. RARE \( D^0 \to \gamma\gamma \) AND \( D^0 \to \pi^0\pi^0 \) DECAYS

In the Standard Model (SM) Flavor Changing Neutral Currents (FCNC) are forbidden at tree-level. These decays are allowed at higher order and have been measured in kaons and \( B \) mesons. For charm mesons the low mass of the down-type companion quark introduces a large suppression at the 1-loop level from the GIM mechanism.
So far no FCNC decays of charm mesons have been observed. The search of rare charmed meson decay such as $D^0 \to \gamma\gamma$ is one possible way to perform that search.

In the SM the process $D^0 \to \gamma\gamma$ is dominated by long distance effects [14]. At short range mainly 2-loops contribute and the branching ratio $B$ of $D^0 \to \gamma\gamma$ is expected to be of the order of $3 \times 10^{-11}$. This is several order of magnitude below the sensitivity of current experiments. But in fact, the transition $D^0 \to \gamma\gamma$ is dominated by Vector Meson Dominance processes (VMD), so that the value of $B(D^0 \to \gamma\gamma)$ is enhanced to $(3.5 \pm 2.6) \times 10^{-8}$. This larger value is confirmed in the HQ$\chi$PT computations that predict $B(D^0 \to \gamma\gamma) = (1.0 \pm 0.5) \times 10^{-8}$.

Such small values are anyhow still a bit far away from experimental capacities. But possible large enhancements arising from long distance New Physics (NP) effects are such that they can lead values as large as $6 \times 10^{-6}$ for $B(D^0 \to \gamma\gamma)$. This is in fact within the reach of present experiments a B-factories. Such effects may for example originate from gluino-exchange within the MSSM framework [15].

The BaBar experiment with about 470 $fb^{-1}$ of data collected near the $\Upsilon(4S)$ resonance has such a discovery potential. This integrated luminosity corresponds to more than $610 \times 10^6$ $c\bar{c}$ quark pairs. The search of the process $D^0 \to \gamma\gamma$ is therefore an appealing, even difficult, mode for NP search. BaBar has effected such an analysis.

The existing upper limit on $B(D^0 \to \gamma\gamma)$ is $2.7 \times 10^{-5}$ at 90% of C.L. [2], and was obtained by the CLEO experiment [16]. The measurement of that branching ratio is normalized to the abundant, pure and precisely measured channel $D^0 \to K^0_S\pi^0$, which branching ratio is equal to $(1.22 \pm 0.5) \times 10^{-2}$ [2]. When employing that technique some systematic uncertainties cancel in the ratio of branching ratio.

The largest background for $D^0 \to \gamma\gamma$ channel is the decay mode $D^0 \to \pi^0\pi^0$. Is presently measured $B$ is equal to $(8.0 \pm 0.8) \times 10^{-4}$ [2]. We also perform similarly the measurement of that latter channel using the normalization technique to the $D^0 \to K^0_S\pi^0$. Doing that measurement at the same time allows to have a better handling of the $D^0 \to \pi^0\pi^0$ background for the search of the $D^0 \to \gamma\gamma$ mode. The main backgrounds for $D^0 \to \pi^0\pi^0$ are the modes $D^0 \to K^0/\bar{K}^0\pi^0$ and $K^-\pi^+\pi^0$.

In order to remove $B\bar{B}$ backgrounds, we use $D^{*+} \to D^0\pi^+$ tagged events and require $P_D > 2.4 - 2.85 GeV/c^2$. We remove QED background by requiring at least 4 tracks or neutrals within the BaBar detector acceptance. The channels $D^{*0} \to D\pi^0/\gamma$ are the largest backgrounds for the normalization channel $D^0 \to K^0_S\pi^0$. Finally in the case of the $\gamma\gamma$ analysis, we perform a veto against photons that can be associated to another photon in the event to build a $\pi^0$ candidate. Such a veto is 66% efficient on $D^0$ signal and removes 95% of the photons originated from $\pi^0$.

For the $D^0 \to \pi^0\pi^0$ analysis the selection efficiencies of the $D^0 \to \pi^0\pi^0$ signal is 15.2% and it is 12.0% for the normalization channel $D^0 \to K^0_S\pi^0$. For the $D^0 \to \gamma\gamma$ analysis the selection efficiencies of the $D^0 \to \gamma\gamma$ signal is 6.1% and it is 7.6% for the normalization channel $D^0 \to K^0_S\pi^0$.

Figure 3 shows the fitted spectra of the $D^0 \to \pi^0\pi^0$ (left) and $D^0 \to \gamma\gamma$ (right) signals.

The $\pi^0\pi^0$ analysis fitted yield is 26010 $\pm 304$ signal events, while for the normalization channel $K^0_S\pi^0$ the yield is 103850 $\pm 392$ events. This corresponds to $B(D^0 \to \pi^0\pi^0) = (8.4 \pm 0.1 \pm 0.4 \pm 0.3) \times 10^{-4}$, where the third uncertainty is related to uncertainty on the world average for $B(D^0 \to K^0_S\pi^0)$ [2]. This measurement is 40% more accurate than the present world average value.

For the $\gamma\gamma$ analysis the fit yields a negative number: $\gamma\gamma - 6 \pm 15$ events. It corresponds to an upper limit of 25.1 events at 90% of C.L. This number converts into an upper limit, computed from pseudo Monte Carlo experiments.
II. SEMI-LEPTONIC BRANCHING RATIO OF THE B0 MESONS AND THE FRACTION $f_s$ ABOVE THE $\Upsilon(4S)$ RESONANCE

As opposed to the semi-leptonic $B_{u,d} \to X l^- \bar{\nu}_l$, that are well known and equal to $(10.99 \pm 0.28)\%$, the existing measurements of the semi-leptonic branching ratio in $B_s$ decays are still inaccurate [2]. It is expected to be from 1.5 to 3% lower than that of $B_u$ [17]. Its world average is $(7.9 \pm 2.4)\%$, from LEP experiment at the Z0 and they include the information on the fraction $P(b \to B_s) = (10.5 \pm 0.9)\%$. The alternate measurement $(10.2 \pm 0.8 \pm 0.9)\%$ is from the $\Upsilon(5S)$ data collected by the BELLE experiment [18]. The LHCb experiment has yet already started to contribute by providing measures of ratios of specific semi-exclusive decays to total inclusive semi-leptonic $B_s$ decay [19].

Recently BaBar collaboration has performed the measurement of $B(B_s \to X l^- \bar{\nu}_l)$ ($B(B_s)_{SL}$) and of $f_s$, the fraction of $B_{u,d}^{0,\pm}$ mesons produced above the $\Upsilon(4S)$ resonance. For this we use $4.1$ fb$^{-1}$ of data from a final energy scan performed in the last period of the data taking in 2008 [20]. In that energy scan, data were collected every 5 MeV above the $\Upsilon(4S)$ resonance, from which $3.15$ fb$^{-1}$ was taken in the range $[2m(B_s), 2m_{Xl}]$.

These 2 measurements are based on the counting of the yield of produced $\phi$ mesons and of $\bar{\phi}$ mesons produced in correlation with a high -momentum lepton. Such signatures are more abundant in $B_s$ decays than in $B_{u,d}$ decays. As a function of the center of mass energy in the scan, one can unfold the 2 parameters $B(B_s)_{SL}$ and $f_s$ from the 3 observables: the number of produced $B$ hadrons, the $\phi$ mesons inclusive rate, and the rate of $\bar{\phi}$ mesons produced in correlation with a high-momentum lepton.

The light $q\bar{q}$ ($q = u, u, s, c$) pair of quarks contribution are subtracted by using data collected 40 MeV below the $\Upsilon(4S)$ resonance. The $B_{u,d}$ contributions are computed from data collected at the $\Upsilon(4S)$ resonance. Many quantities derived from the PDG [2] such as $B(B_s \to D_s X), B(D_s \to X l^- \bar{\nu}_l), B(D_s \to \phi X), B(D_s \to \phi X l^- \bar{\nu}_l)$ (...) are exploited in the computation of $B(B_s)_{SL}$ and $f_s$ from the above enumerated 3 observables. The input $B(B_s \to D_s X)$ is from the less accurately known of the various input parameters. Its present world average is $(93 \pm 25)\%$.

Figure 4 displays the fitted value of $B(B_s)_{SL}$ with respect to $B(B_s \to D_s X)$ (left) and of $f_s$ versus the value of the center of mass energy of the 2008 PEPI-II scan (right). We measure $B(B_s)_{SL} = (9.9_{-2.1}^{+2.6}(stat.)_{-0.7}^{+1.3}(syst.))\%$. This branching ratio is consistent with previously mentioned measurements. The values of $f_s$ for bins near the $\Upsilon(5S)$ resonance are fully compatible with those obtained by BELLE: $(18.0 \pm 1.3 \pm 3.2)\%$ and CLEO: $(16.8 \pm 2.6_{-3.4}^{+6.7})\%$ in 2007 [21].
FIG. 4: Fitted value of $B(B_s \to \phi \ell \nu)$ with respect to $B(B_s \to D_s X)$ (left) and of $f_s$ versus the value of the center of mass energy of the 2008 BaBar scan (right) [20]. The statistical and additional systematic uncertainties are plotted separately.

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