NEW QUARKONIUM RESULTS FROM THE BABAR EXPERIMENT

N. ARNAUD, representing the BaBar Collaboration
Laboratoire de L’Accélérateur Linéaire, IN2P3/CNRS et Université Paris XI,
F-91898 Orsay Cedex, France

New BaBar results on B mesons and quarkonia are presented: an analysis of $B^+ \to X(3872)K^+$ and $B^0 \to X(3872)K^0$ decays with $X(3872) \to J/\psi \pi^+ \pi^-$, a precise measurement of the $B$ mass difference $\Delta m_B = m(B^0) - m(B^+)$ and a study of hadronic transition between $\Upsilon$ mesons.

1 Introduction

With the end of the data taking phase, the BaBar collaboration is now entering a intensive phase of analysis aiming at exploiting the huge $\Upsilon(4S)$ data sample collected. The studies presented here benefit from the large $b\bar{b}$ and $c\bar{c}$ cross-sections and provide several new or improved measurements in the quarkonium area. They all have been optimized keeping the signal regions blind. In addition, a new measurement of the $B$ mass difference is presented.

2 Study of the decays $B \to X(3872)K$ with $X(3872) \to J/\psi \pi^+ \pi^-$

The $X(3872)$ state, discovered by the Belle collaboration, does not match any predicted charmonium state: many theoretical ideas have been proposed to explain its existence. The mass of this narrow resonance, $\Gamma_X < 2.3 \text{ MeV}/c^2$ at 90% confidence level (C.L.), is barely above the $D^0 D^{*0}$ threshold: $m_X = 3871.4 \pm 0.6 \text{ MeV}/c^2$. Although its decay to this state has been observed, the measured mass is significantly higher (about $3 \text{ MeV}/c^2$); whether this discrepancy is the sign of two distinct states or a threshold effect is still unclear. The $X(3872)$ quantum numbers are not known although its parity should be positive, and angular analyses favour $J^{PC} = 1^{++}$ or $2^{-+}$.

Figure 1: Fits to the $m(J/\psi \pi^+ \pi^-)$ data distributions of (left) $B^+ \to X(3872)K^+$ and (right) $B^0 \to X(3872)K^0_S$ candidates. The dashed (solid) line represents the background (sum of background plus signal) probability density function. The statistical significances w.r.t. the null signal hypothesis are $8.6\sigma$ and $2.3\sigma$ respectively.
The decays $B \rightarrow X(3872)K$ with $X(3872) \rightarrow J/\psi \pi^+\pi^-$ are studied on the full BaBar dataset (413 fb$^{-1}$). Signal events are discriminated from background using two kinematical variables: the energy difference $\Delta E = E_B - \sqrt{s}/2$ and the beam-energy substituted mass $m_{ES} = \sqrt{s}/4 - \left(\vec{p}_B\right)^2$ where $(E_B, \vec{p}_B)$ is the $B$ 4-momentum vector in the $\Upsilon(4S)$ rest frame. $\Delta E (m_{ES})$ peaks at 0 ($m_B$) for signal with a resolution of a few tens of (a few) MeV. In addition, event-shape variables reject random combinations of particles coming from continuum $(q\bar{q})$ events.

The numbers of signal events for the charged and neutral modes are extracted by an unbinned maximum likelihood (UML) fit of the $X(3872)$ reconstructed mass in the $m_{ES}$ signal region. $B \rightarrow \psi(2S)K$ with $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ decays are used as a control sample (same final state, close mass and very narrow state) to validate the fitting procedure and estimate biases. For both modes, the dominant systematics come from the background modeling and the secondary branching fractions. For the neutral mode, the fit convergence is ensured by fixing the resonance width to the value obtained from the charged mode fit, which induces the largest systematics. The results are:

\[
\frac{\mathcal{B}(B^0 \rightarrow X(3872)K^0)}{\mathcal{B}(B^+ \rightarrow X(3872)K^+)} = \frac{(3.5 \pm 1.9 \pm 0.4) \times 10^{-6}}{(8.4 \pm 1.5 \pm 0.7) \times 10^{-6}} = 0.41 \pm 0.24 \pm 0.05 < 0.73 \text{ at 90}\% \text{ C.L.} \quad (1)
\]

Still using the $\psi(2S)$ control sample, the mass difference of the $X(3872)$ states produced in $B^0$ and $B^+$ decays is found to be $2.7 \pm 1.6 \pm 0.4$ MeV$^2$. These results are consistent with either the molecular$^9$ or diquark-antidiquark$^{10}$ model within two standard deviations. Finally, an updated upper limit of the $X(3872)$ natural width is set to $\Gamma_X < 3.3$ MeV/c$^2$ (90%, C.L.).

### 3 Measurement of the $B$ mass difference

The neutral-to-charged mass difference of $B$ mesons probes Coulomb contributions to their quark structures and is needed to determine $B^+$ and $B^0$ decay fractions at $B$-factories. To improve its accuracy (much worse$^2$ than for the $\pi$, $K$ and $D$ mesons), a method based on the analysis of momentum spectra in the decays $B \rightarrow J/\psi K$ has been applied$^{11}$ on a sample of 230 million $B\bar{B}$ events. In the center-of-mass frame (related quantities labeled with a $^*$), one has:

\[
\Delta m_B \equiv m(B^0) - m(B^+) = -\left[p^*(B^0) - p^*(B^+)\right] \frac{p^*(B^0) + p^*(B^+)}{m(B^0) + m(B^+)} \quad (2)
\]

As the $B\bar{B}$ threshold is very close to the $\Upsilon(4S)$ mass, $B$ mesons have low $p^*$ which makes the right-most factor of Eq. $^2$ almost constant. Hence, $\Delta m_B$ can be extracted from the mean values of the $p^*$ spectra. The resolution depends on the accelerator energy spread and on the reconstruction whose resolutions are about 40 MeV/c and 15 MeV/c respectively for the clean selected decay modes: $B^0 \rightarrow J/\psi K^+\pi^-$ and $B^+ \rightarrow J/\psi K^+$, where $J/\psi \rightarrow \mu^+\mu^- \text{ or } e^+e^-$. The size of a possible bias induced by the mean-$p^*$ method has been estimated by MC simulations. The influence of the beam energy smearing and of the $\Upsilon(4S)$ lineshape is studied using a simulation without detector. Varying the parameter$^{12}$ and choosing $\Delta m_B = 0.3$ or 0.4 MeV/c$^2$, the measured mass differences are within 2% of the input values. The detector contribution to the bias is computed using a full MC simulation of generic $B\bar{B}$ decays and leads to the dominant systematics. Other important systematics errors are coming from the choice of the fit functions, both for the background and the signal species.

$J/\psi$ decays to $\mu^+\mu^-$ and $e^+e^-$ are dealt with separately to account for bremsstrahlung in the second channel. The selections are based on BaBar particle-identification selectors, event-shape variables and $\Delta E$. The $B^0$ and $B^+$ samples are fitted simultaneously as the common effect of the PEP-II energy spread dominates the $p^*$ distribution shapes. The two $p^*$ mean differences are consistent and can then be combined. Adding systematics errors, one finally gets:
\[ \Delta p^* = ( -5.5 \pm 0.8 \pm 0.5 ) \text{MeV}/c \Rightarrow \Delta m_B = ( +0.33 \pm 0.05 \pm 0.03 ) \text{MeV}/c^2 \]  

(3)

The measured \( B \) mass difference is compatible with the current world average\(^2\) with errors reduced by a factor 4. Consequently, the significance of \( \Delta m_B \) being positive exceeds the 5\( \sigma \) level. Using this measurement to compute the associated contribution to the ratio of \( \Upsilon(4S) \) decay rates to charged and neutral \( B \) pairs gives a value compatible with the experimental results\(^2\) unknown Coulomb contributions to the quark structure\(^13\) are not visible yet.

### 4 Hadronic transitions between \( \Upsilon \) states

The \( b\bar{b} \) system offers unique opportunities to study hadronic transitions between \( \Upsilon \) states with 5 known (4 allowed but not observed so far) transitions with 2 charged pions (1 \( \eta \) meson) in the final state. Experimental results allow to test the QCD Multipoles Expansion model\(^14\).

\( \Upsilon(4S) \) hadronic transitions are searched in a large data sample: 347 \( \text{fb}^{-1} \) recorded at the resonance peak (‘onpeak’) and 37 \( \text{fb}^{-1} \) taken 40 MeV below (‘offpeak’ data used as control sample). \( \Upsilon(2S) \) and \( \Upsilon(3S) \) transition studies are based on onpeak data with initial state radiation. \( \Upsilon(nS) \rightarrow \mu^+\mu^- \) or \( e^+e^- \) are processed separately to account for trigger efficiency differences and \( e^- \) bremsstrahlung. For \( \eta \) channels, decays to \( \pi^+\pi^-\pi^0 \) are reconstructed: the trigger efficiency is much larger than for the \( \eta \rightarrow \gamma\gamma \) mode and all final states have the same charged particles, which cancels out several systematics for partial width ratios. Signal events are identified by requiring compatibility between the invariant lepton pair mass \( M_{ll} \) and the known mass of a \( \Upsilon(nS) \) resonance. For \( \pi^+\pi^- \) channels, the invariant mass difference \( \Delta M = M_{\pi\pi ll} - M_{ll} \) between the final state and the leptons must also match the difference between the masses of the initial and final \( \Upsilon \) states. For decays involving an \( \eta \) meson, the mass difference takes into account the additional constraint: \( \Delta M_\eta = M_{3\pi ll} - M_{ll} - M_{3\pi} \), with \( M_{3\pi} \) being the mass of the \( \eta \) candidate.

The statistical significances w.r.t. the null signal hypothesis are 11\( \sigma \) and 6.2\( \sigma \) respectively.

The efficiency-corrected signal yields for the known \( \Upsilon(mS) \rightarrow \Upsilon(nS)\pi^+\pi^- \) transitions are determined without any assumption on the decay angular distribution. Candidates are clas-
New and improved measurements in the quarkonium area have been presented by the Belle Collaboration. They cover a wide range of topics: the new $X(3872)$ state, the $B$-mass difference and the hadronic transitions between $\Upsilon$ states.

### 5 Conclusion

New and improved measurements in the quarkonium area have been presented by the BaBar collaboration. They cover a wide range of topics: the new $X(3872)$ state, the $B$-mass difference and the hadronic transitions between $\Upsilon$ states.

### References

1. S.K. Choi et al (Belle Collaboration), $e^{-}$ Phys. Rev. Lett. 91, 262001 (2003).
2. Particle Data Group: Y.-M. Yao et al, J. Phys. G33, 1 (2006) and 2007, partial update for the 2008 edition.
3. S.K. Choi et al (Belle Collaboration), $e^{-}$ Phys. Rev. Lett. 97, 162002 (2006).
4. B. Aubert et al (BaBar Collaboration), $e^{-}$ Phys. Rev. D 77, 011102 (2008).
5. W. Dunwoodie and V. Ziegler, $e^{-}$ Phys. Rev. Lett. 100, 062006 (2008).
6. B. Aubert et al (BaBar Collaboration), $e^{-}$ Phys. Rev. D 74, 071101 (2006).
7. D. Acosta et al (CDF Collaboration), $e^{-}$ Phys. Rev. Lett. 98, 132002 (2007).
8. B. Aubert et al (BaBar Collaboration), [arXiv:0803.2838](http://arxiv.org/abs/hep-ex) accepted for publication in $e^{-}$ Phys. Rev. D-RC.
9. E. Braaten and M. Kusunoki, $e^{-}$ Phys. Rev. D 71, 074005 (2005).
10. L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, $e^{-}$ Phys. Rev. D 71, 014028 (2005).
11. B. Aubert et al (BaBar Collaboration), [arXiv:0805.0497](http://arxiv.org/abs/hep-ex) submitted to $e^{-}$ Phys. Rev. D-RC.
12. B. Aubert et al (BaBar Collaboration), $e^{-}$ Phys. Rev. D 72, 032005 (2005).
13. S. Dubynskiy et al, $e^{-}$ Phys. Rev. D 75, 113001 (2007) and references therein.
14. Y. P. Kuang, Front. Phys. China 1, 19 (2006) and references therein.