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Spectroscopy results from *BABAR*

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This paper intends to briefly summarize the recent results in Spectroscopy, published by the *BABAR* Collaboration. The *BABAR* experiment was a B-factory, at SLAC, where asymmetric energy beams of electron-positron were accelerated and collided at the energy in the center of mass of Υ(4S). In 9 years of data taking *BABAR* collected 433 fb^{-1} equivalent luminosity on-peak-data at the Υ(4S) energy, 30 fb^{-1} data at the Υ(3S) energy, 15 fb^{-1} data at the Υ(2S) energy, and a scan about Υ(4S) was done, collecting 25 pb^{-1} every 5 MeV. Thanks to the high luminosity achieved, it is possible to perform high precision measurements, and spectroscopy studies. An update on the measurement of the X(3872) using the entire available dataset will be given, and the new results on the decay $X(3872) \to J/\psi\omega$ are shown. A short overview of the results on X, Y particle studies from B decays at *BABAR* is given. Recent preliminary results on the D states are summarized: precise measurements of mass and width are provided in this case. As conclusion, new analysis on bottomonium decays are presented.

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1. Introduction

For a long time the physics of quarkonium remained a seemingly well-understood field, where the theory described experimental results quite well. Over the past few years, a new era of spectroscopy has begun, thanks to copious surprising results obtained mostly at the B-factories, where huge amount of collected data have been used for various charmonium-production mechanism and spectroscopy searches. Spectroscopy is one of the most interesting issue, in particular from the discovery of the resonant state X(3872). In fact, several new observed states do not fit theoretical expectations. As consequence, many interpretations like HQT, Chiral Simmetry, quark model, bag model, molecular or tetraquark interpretations, etc.etc.[1], were proposed from theorists, to try to understand if all these resonant states are pieces of the same puzzles, or a hint of something new.
Spectroscopy studies in *BABAR* are performed in:

- production in continuum, using data collected at the energy in the center of mass of Υ(4S);
- B decays analysis (color-suppressed b-decays and open-charm physics);
- bottomonium transitions;
- double photon production.

Below some experimental results of the studies performed by the *BABAR* collaboration are presented.

2. $B \to X, Y\ K$

The so called X(3872) is the first non-expected state, observed in the invariant mass $J/\psi\pi^+\pi^-$ mass from B decays at *Belle*[2], then confirmed from *CDF*[3], D0[4] and *BABAR* [5]. In *BABAR* this analysis was repeated on the full dataset, showing a mass shift Δm_X between the mass measurements of the charged and the neutral B channel ($B^\pm \to XK^\pm$ and $B^0 \to XK^0_S$, respectively, with $X \to J/\psi\pi^+\pi^-$), equal to $(2.7 \pm 1.6 \pm 0.4)$ MeV/c^2. The Branching Fraction (BF) measurements confirm the results obtained in the previous analysis performed by *BABAR* , as detailed in Ref.[6]. Also the ratio between the BR of the charged and the neutral B decay channel was measured, equal to $(0.41 \pm 0.24 \pm 0.05)$. The mass shift and the ratio as mentioned are important measurements, in order to give some theoretical explanation of what the state X(3872) is. Some plots related to the X(3872) analysis are shown in Fig. 1(a, b), where a very narrow but evident peak is shown for the charged B channel (with 8.6σ significance), while only 2.3σ significance was measured in the neutral channel.
Acutually the state X(3872) is seen in several decay modes: $B \to XK$, $X \to J/\psi\pi^+\pi^-$[5], $X \to \bar{D}^{*0}D^0$[6, 7], $X \to J/\psi\gamma$[8], $X \to \psi(2S)\gamma$[9], and the most recent $X \to J/\psi\omega$[10].In the same B decay mode *BABAR* observed also another resonant state: Y(3940)[11]. An eccess of events was reported by the *Belle* collaboration in the invariant mass of 3 pions above 750 MeV/c^2. As $|m_{J/\psi 3\pi} - 3872| < 16.5$ MeV/c^2, it was interpreted as X(3872).

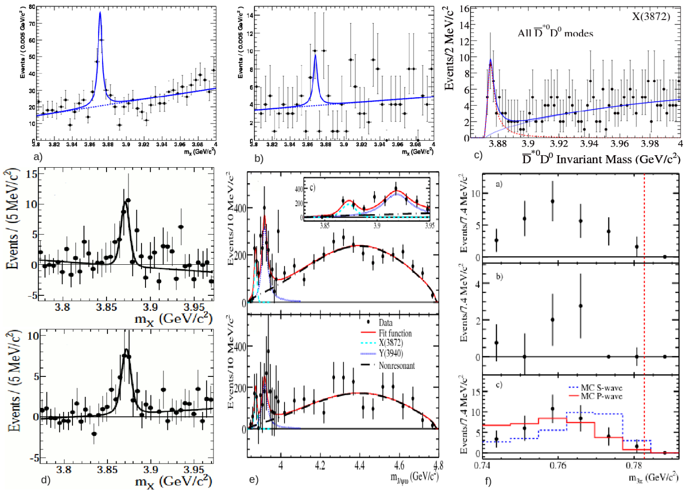

Figure 1: Distribution of $X(3872) \to J/\psi\pi^+\pi^-$ (a) in the charged and (b) neutral B decay mode; (c) $X(3872) \to \bar{D}^{*0}D^0$; (d) $X(3872) \to J/\psi\gamma$ (top); (d) $X(3872) \to \psi(2S)\gamma$ (bottom); (e) $X(3872)$ and $Y(3940)$, decaying to $J/\psi\omega$; (f) angular distribution of $X(3872) \to J/\psi\omega$, with the hypothesis of S- and P-waves obtained from MC simulations. Data are represented as black spots in the plot labeled by (f).

BABAR confirmed the existence of Y(3940) in that analysis, and there is a more recent update where the evidence of a peak of 4σ significance in $0.7695 < m_{3\pi} < 0.7965$ GeV/c^2 was found[10]. A study of the angular distribution was performed by comparing the data with a simulation of X(3872) distributions in S- and P-waves hypotheses. The plot in Fig. 1 shows that the state X(3872) is more likely $J^P = 2^-$ than $J^P = 1^+$ (χ^2 probability is 62 % against 7 %). A Dalitz weighting technique was used to perform this study.

Concerning the C-parity study of the state X(3872), this narrow state is expected to have ispospin I = 1. In fact, the $\pi^+\pi^-$ invariant mass is compatible with the ρ mass, in the analysis of $B \to X(3872)K$, with $X(3872) \to J/\psi\pi^+\pi^-$, this narrow state is expected to have ispospin I = 1. But the search for charged X partners have found no evidence([14, 12]); then, we can conclude that X(3872) is an isospin violating state, with I = 0 favored. An interesting result related to the X(3872) analysis is reported in Ref.[8, 9], where the analysis of the invariant mass $J/\psi\gamma$ and $\psi(2S)\gamma$, compatible with X(3872) mass and width, leds to the conclusion that the C-parity of the X(3872) state is positive. The mass of $X \to J/\psi\gamma$ and $X \to \psi(2S)\gamma$ were measured with 3.6σ and 3.5σ significance, respectively.

Surprising results related to the X(3872) analysis still come from the paper quoted in Ref.[13], where the analysis of the invariant mass $D^{0(*)}\bar{D}^{0(*)}$ in B decays is performed, as shown in Fig. 1(c). This analysis reports a mass shift Δm_X, from the mass world average of $X \to J/\psi\pi^+\pi^-$, equal to 4.5σ significance. Although at the beginning *BABAR* and *Belle* were in agreement on this result, recently there was an update from Belle concerning this analysis[15], showing that they disagree on the *BABAR* BR measurements of $B \to XK$, with $X \to D^0\bar{D}^0$, and the mass measurements of the X(3872) state, too. They have now confirmed a good agreement between the mass measurement of X(3872) in decays to both, $J/\psi\pi^+\pi^-$ and $D^0\bar{D}^0$. However, several authors have proposed explanations for the mass shift as mentioned. A possible explanation for the *BABAR* mass shift measurement is that the peak position is sensitive to the angular momentum due to the proximity of the threshold.

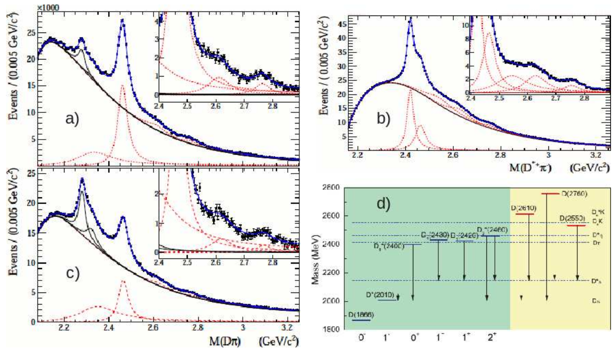

Figure 2: Invariant mass distribution of (a) $D^+\pi^-$, (b) $D^0\pi^-$, (c) $D^0\pi^+$; (d) plot showing the mass spectrum as function of J^P.

A mass shift of about 3 MeV/c^2 is expected if X(3872) is a state with the quantum number J^P = 2^-, for instance. If the X(3872) just below the threshold, the lineshape could create an artificial peak above the threshold, which is the one measured experimentally, and its parameters would not correspond to the real particle properties.
The explanation of the state X(3872) is still now rather difficult, as there is still no satisfactory $c\overline{c}$ assignment for this resonance.

3. Observation of the new D states

By analyzing the process $e^+e^- \to c\overline{c} \to D^{**}X \to D(*)\pi X$, the *BABAR* collaboration found 4 new states in D spectrum: two of them were found in D-waves (width about 40 MeV), and two are in S-waves (width much larger: it is about 300 MeV). In Fig. 2 the main plots related to this interesting study are reported. For the first time candidates for the radial excitations of D^0, D^{0*} and D^+ have been observed, as well as the L=2 excited states of D^0 and D^{0*}. These results were presented at ICHEP 2010, this year. They are important to determine precise measurement of mass and width of these new D states[16]. We denote them as $D(2550)^0$, $D^*(2600)^0$, $D(2750)^0$, $D^*(2760)^0$. We also observed the isospin charged partners $D^*(2600)^+$ and $D^*(2760)^+$. It was observed that the states $D(2550)^0$, $D^*(2600)^0$ have the same value and helicity-angular distribution consistent with the predicted radial excitation $D_0^1(2S)$ and $D_1^3(2S)$.

4. Bottomonium search at *BABAR*

Recently at *BABAR* it has been possible to start bottomonium search, that is even more interesting because of copious J^{PC} = 1^{--} production in e^+e^- annichilation, when $\sqrt{s} = Mass(\Upsilon)$. The search for light Higgs and bottomonium states was the main reason why in *BABAR* the decision to run at the energy of $\Upsilon(3S)$ and $\Upsilon(2S)$ was taken. The *BABAR* experiment collected the largest $\Upsilon(3S)$ data sample in the world: 120M of $\Upsilon(3S)$ and 100M of $\Upsilon(2S)$ were collected. Althought *BABAR* did not collect data at $\Upsilon(1S)$ center of mass energy, we can access those events by using di-pion tag by mean of $\Upsilon(2S)$ and $\Upsilon(3S)$ events.

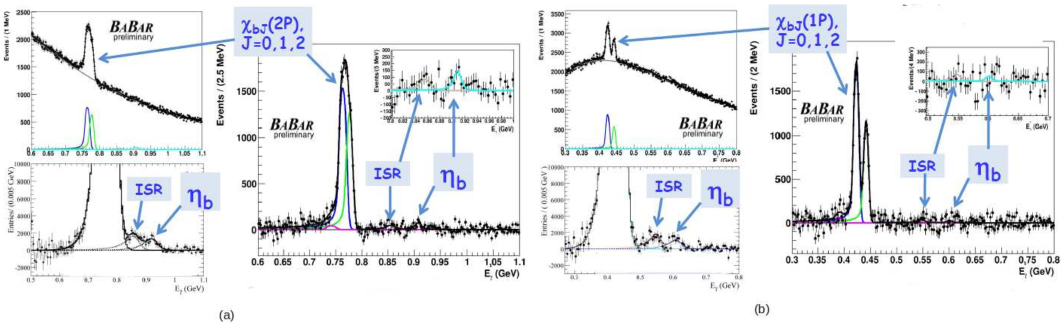

Figure 3: Study of η_b in the photon conversion, using (a) the data collected at $\Upsilon(3S)$ and (b) the data collected at $\Upsilon(2S)$.

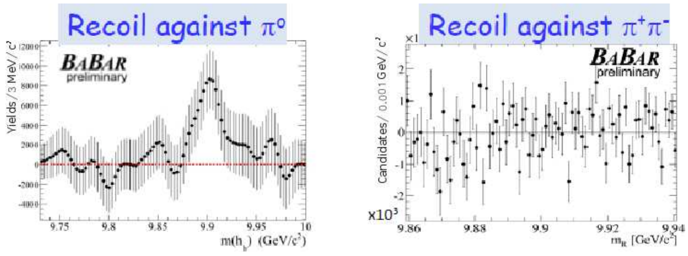

Figure 4: h_b study: recoil against π^0, and against $\pi^+\pi^-$ mass.

The ground state (S, L=0), known as η_b, was observed for the first time at *BABAR* [17]. In this paper a new result of the η_b measurement will be given, using $\gamma \to e^+e^-$ conversion. In Fig. 3(a) the main results of the analysis performed by using the $\Upsilon(3S)$ data are shown, and in Fig. 3(b) the main results of the analysis performed by using the $\Upsilon(2)$ data are shown. Both studies are new, and they were performed in inclusive photon spectrum.
The state called h_b corresponds to the quantum numbers S=0, L=1. In *BABAR* we looked for h_b in the decay $\Upsilon(3S) \to \pi^0 h_b$ and $\Upsilon(3S) \to \pi^+\pi^- h_b$, which are favored production mechanism[18]. The expected h_b decays are: $h_b \to \gamma\eta_b$, h_b to 3 gluons, and h_b to 2 gluons and one photon[19]. No signal was found in $\Upsilon(3S) \to \pi^+\pi^- h_b$, while in the study of the π^0 recoil an effect of approximatively 3σ significance (Fig. 4).

New observation of a triplet state (S=1, L=2) was performed in *BABAR* . The predicted mass was (10160 $\pm$ 10) MeV/c^2, and the predicted separation among the 3 D-states is 5-12 MeV[20]. By analyzing the transition $\Upsilon(1^3D_J) \to \pi^+\pi^-\Upsilon(1S)$, *BABAR* found a mass value equal to $m_{\Upsilon(1^3D_J)}$ = (10164.5 $\pm$ 0.8 $\pm$ 0.5) MeV/c^2[21], consistent with the value measured by CLEO[22]. In Fig.5 we report the main plot of this study, where six different cascades were observed, decaying to the same final state. This measurement is important, because it represents the first observation of hadronic decays of a $\Upsilon(1^3D_J)$ state. A study related to the determination of the quantum numbers of the D states has been performed: it concludes that it is most likely J^P = 2$^-$.

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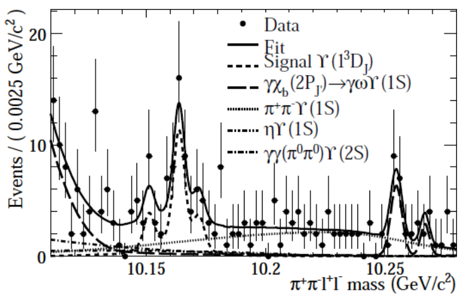

Figure 5: Invariant mass distribution of $\pi^+\pi^-l^+l^-$, showing the 3 D states in the transition $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$.

Before concluding this short summary of the recent spectroscopy results at *BABAR* , it is worth to spend some words on the analysis $\Upsilon(1S) \rightarrow$ invisible. In the previous *BABAR* analysis, the process $\Upsilon(3S) \rightarrow \gamma A^0$, A^0 to invisible, was under study[23]. A new strategy is now used: the transition $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ is examinated, as reported in Ref.[24].

5. Conclusion

Althought the *BABAR* experiment stopped to collect data in April 2008, there are many ongoing analysis, most of them in the field of Spectroscopy. This short report showed several new interesting results, especially in the study of the D states in B decays, and the new hadronic decay of $\Upsilon(1^3D_J)$ in bottomonium spectroscopy. The challenge of X(3872) interpretation seems to still be opened, after 7 years from its discovery: a B-factory like *BABAR* can give its contribution, thanks to the huge amount of data collected in the past years. We are waiting for the winter conferences to show other new exciting results.

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