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Charm and charmonium spectroscopy at B-factories

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We report on most recent Charm and Charmonium spectroscopy results from the B-factories.

1 Introduction

Since a few years, charm and charmonium spectroscopy has revived, both from experimental and theoritical point of views. Many new states have been discovered triggering numerous theoritical publications. The B-factories with their large enriched charm sample have played a leading role on the experimental side with the observation and study of most of the new states. Other experiments such as CLEO and CDF have also contributed. Classical hadron spectroscopy predicted some of these new states, but not all of them. Therefore a lot of effort have been spent in order to understand the nature of the later. We are summarizing here the most recent and important results in hadron spectroscopy, including strange-charm mesons, charm baryons and charmonium and charmonium-like states.

2 Strange-charm mesons D_s

Prior to the B-factories, only 4 strange-strange mesons had been observed: the S-wave states $D_s(1968)^+$ ($J^P = 0^-$) and $D_s(2112)^{*+}$ ($J^P = 0^-$), and the P-wave states $D_{s1}(2536)^+$ ($J^P = 1^+$) and $D_{s2}(2573)^{*+}$ ($J^P = 2^+$). In 2003, the CLEO[1] and Babar[2] collaborations reported two states, the $D^*_{sJ}(2317)^+$ and the $D_{sJ}(2460)^+$, in continuum production ($e^-e^+ \to c\bar{c}$). These two states were subsequently observed by Belle[3] as wells as in B decays. The masses of the states were actually below expectations so there were a lot a speculation whether they were the missing 0^+ and 1^+ levels, other ($c\bar{s}$), or exotic states. The $D^*_{sJ}(2317)^+$ has been observed only in the $D_s^+\pi^0$ decay mode, while the $D_{sJ}(2460)^+$ has been seen in the $D_s^{*+}(D_s^+\gamma)\pi^0$, $D_s^+\gamma$ and $D_s^+\pi^+\pi^-$ decay modes. Belle[3] and Babar[4] have performed angular analysis of the $D_{sJ^*}(2317)^+ \to D_s^+\pi^0$ and $D_{sJ}(2460)^+ \to D_s^+\gamma$ decays and have shown that the two states are consistent with $J = 0$ and $J = 1$, respectively. A negative parity of the $D_{sJ}(2460)^+$ has been ruled out by an angular analysis of the $D_{sJ}(2460)^+ \to D_s^{*+}\pi^0$ decay mode. Searches for isospin partners as well as for doubly charged states and different decay modes[5] have been carried out. No signal has been

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found. All results indicate that the $D^*_{sJ}(2317)^+$ and the $D_{sJ}(2460)^+$ are indeed the missing 0^+ and 1^+ levels.

In 2006, Babar has reported the observation of a new D_s meson [6] decaying into D^0K^+ and D^+K_s with a mass $m = (2856.6 \pm 1.5 \pm 5.0) MeV/c^2$ and a width $\Gamma = (48 \pm 7 \pm 10) MeV$, where the first error is statistical and second is systematic. The new state has been observed in two inclusive continuum processes $e^+e^- \rightarrow D^0K^+X$ with $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0$ and $e^+e^- \rightarrow D^+K_SX$ with $D^+ \rightarrow K^-\pi^+\pi^+$. The mass spectra of the three D decay present similar features: a peak at $2.4 GeV/c^2$ due to a reflection of the $D_s(2536)^+$, a clear signal from the $D_s(2573)^+$, a broad structure peaking at a mass of approximately 2700 MeV/c^2 and a signal enhancement due to the new state $D_s(2860)^+$. The broad structure at 2700 MeV/c^2 is fitted with a mass $m = (2688 \pm 4 \pm 3) MeV/c^2$ and a width $\Gamma = (112 \pm 7 \pm 36) MeV$.

This later state was clearly observed in $B^+ \rightarrow \bar{D}^0D_{sJ} \rightarrow \bar{D}^0D^0K^+$ decay by the Belle collaboration [7]. It was then assigned to a new D_{sJ} meson, the $D_{sJ}(2700)$. The Dalitz plot analysis shows that the decay $B^+ \rightarrow \bar{D}^0D^0K^+$ proceeds dominantly through quasi-two-body channels: $B^+ \rightarrow \bar{D}^0D_{sJ}(2700)^+$ and $B^+ \rightarrow \psi(3770)K^+$. The measured mass and width are $m = (2715 \pm 11^{+11}_{-14}) MeV/c^2$ and $\Gamma = (115 \pm 20^{+36}_{-32}) MeV$, respectively. The helicity angle distribution favors $J = 1$.

Babar has searched for resonances in $B \rightarrow \bar{D}^{(*)}D^{(*)}K$ decays, in 22 decay modes. The DK and D^*K invariant mass distributions have been built summing up all 8 corresponding B decay modes in each case. Both distributions present a clear enhancement near 2700 MeV/c^2. However, due to an unknown structure at low mass in the DK invariant mass distribution and to the possible presence of additional resonances in the signal region in the D^*K invariant mass distribution, no attempt has been made to extract the parameters of the the $D_{sJ}(2700)$. A full Dalitz plot analysis is undergoing.

3 Charmonium(-like) states

The X(3872) was discovered by Belle [8] in $B^+ \rightarrow X(3872)K^+$ with $X(3872) \rightarrow J/\psi\pi^+\pi^-$. It was confirmed [9] by CDF, D0 and Babar. There have been many speculations about the nature of this state: conventional charmonium state, charmonium hybrid, diquark-antidiquark state [10], or $D^0\bar{D}^{*0}$ molecule [11]. At present none of the hypothesis is favored. The current mass and width are $m = (3871.2 \pm 0.5) MeV/c^2$ and $\Gamma < 2.3 MeV$ (90% CL). Babar has found no evidence of a charged parnter. Belle [12] has shown that the $\pi\pi$ invariant mass distribution favors positive parity $P = +1$. The CDF collaboration [13] has performed an angular analysis of the $X(3872) \rightarrow \pi^+\pi^-$ decay and demonstrated that quantum numbers $J^{PC} = 1^{++}$ are favored. In parallel, Belle [14] and Babar [15] have observed the decay $X(3872) \rightarrow J/\psi\gamma$ which indicates that the charge conjugation number is $C = +1$.

Recently, Belle [16] has observed an enhancement in the $D^0\bar{D}^0\pi^0$ system from $B \rightarrow D^0\bar{D}^0\pi^0K$ decay. The enhancement peaks at a mass $m = (3875.4 \pm 0.7^{+1.2}_{-2.0}) MeV/c^2$. Babar confirmed this observation in the following decays: $B^{+/0} \rightarrow \bar{D}^0D^{*0}K^{+/0}\mathrm{and} B^{+/0} \rightarrow \bar{\mathrm{D}}^{*0}\mathrm{D}^0\mathrm{K}^{+/0}$ with $D^{*0} \rightarrow D^0\pi^0$ and $D^{*0} \rightarrow D^0\gamma$. The ratio of neutral to charged modes branching fractions is $R = 2.23 \pm 0.93 \pm 0.55$. The combined mass from all 4 modes is $m = (3875.6 \pm 0.7^{+1.4}_{-1.5}) MeV/c^2$. Therefore, the mass measurements from Belle and Babar are in very good agreement. However, it is more than 2.5 standard deviations above the mass of the X(3872). Are they the same states or is the state at 3875 MeV/c^2 a new resonance?

Babar [17] has recently discovered a new state, the Y(4260) decaying in to $J/\psi\pi^+\pi^-$, in the initial state radiation process $e^+e^- \rightarrow \gamma_{ISR}J/\psi\pi^+\pi^-$. The measured mass and width are $m = (4259 \pm 8 \pm 4) MeV/c^2$ and $\Gamma = (88 \pm 23 \pm 5) MeV$, respectively. The quantum numbers are straigthforward: $J^{PC} = 1^{--}$. This state is still the subject of many theory papers attempting to explain its nature: classical charmonium state, tetraquark [18], or hybrid charmonium [19,20,21].

The Y(4260) was subsequently observed by the Cleo-c [22], Cleo-III [23] and Belle collaborations [24]. Belle's mass measurement is higher compared to Babar: $m = (4295 \pm 10^{+11}_{-5}) MeV/c^2$ with $\Gamma = (133^{+26+13}_{-22-6}) MeV$.

Babar has been searching for $Y(4260) \to \psi(2S)\pi^+\pi^-$ decay [25]. The observed $\psi(2S)\pi\pi$ invariant mass distribution shows an enhancement that is not compatible with the Y(4260), but with a higher mass resonance. Assuming the enhancement is due to a single resonance, the parameters of this resonance would be $m = (4324 \pm 24) MeV/c^2$ and $\Gamma = (172 \pm 33) MeV$ where the errors are statistical only. We shall note that this enhancement is compatible with the Y(4260) from Belle which measures a higher mass.

Finally, Belle has been reporting three states near $3940 MeV/c^2$. The Z(3930) has been observed [26] in $\gamma\gamma \to D\bar{D}$, with a mass $m = (3929 \pm 5 \pm 2) MeV/c^2$ and a width $\Gamma = (29 \pm 10 \pm 2) MeV$. The angular distribution of the decay strongly favors $J = 2$. This state is interpreted as the $(c\bar{c})$ $2^3P_2(2^{++})$ state (the χ'_{c2}). The Y(3940) has been observed [27] in B decays $B \to J/\psi\omega(\pi\pi\pi)K$, with a mass $m = (3943 \pm 11 \pm 13) MeV/c^2$ and a width $\Gamma = (87 \pm 22 \pm 26) MeV$. This state has been tentatively assigned to the $(c\bar{c})$ $2^3P_1(1^{++})$ state (the χ'_{c1}) [28]. The X(3940) has been observed [29] in continuum production, in the recoil of a J/ψ: $e^+e^- \to J/\psi X$, with a mass $m = (3943 \pm 6 \pm 6) MeV/c^2$ and a width $\Gamma = (15.4 \pm 10.1) MeV$, and in the $X \to D\bar{D}^*$ decay mode. This state is likely to be the $(c\bar{c})$ $3^1S_0(1^{++})$ state (the $\eta_c(3S)$) [28].

4 Charm baryon

With the discovery of the Ω_c^* [30], all nine $J^P = \frac{1}{2}^+$ and six $J^P = \frac{3}{2}^+$ ground states ($L = 0$) have now been observed. Several orbitally excited states have already been seen as well.

Babar [31] has observed a new state, the $\Lambda_c(2940)^+$, decaying into D^0p, with a mass $m = (2939.8 \pm 1.3 \pm 1.0) MeV/c^2$ and a width $\Gamma = 17.5 \pm 5.2 \pm 5.9 MeV$. In this decay mode, Babar confirms the previously reported [32] $\Lambda_c(2880)^+$ (seen in $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$), with a mass $m = (2881.9 \pm 0.1 \pm 0.5) MeV/c^2$ and a width $\Gamma = (5.8 \pm 1.5 \pm 1.1) MeV$. The two states have also been reported by Belle [33], in $\Lambda_c^+\pi^+\pi^-$, with masses and widths $m = (2881.2 \pm 0.2^{+0.4}_{-0.3}) MeV/c^2$ and $\Gamma = (5.5^{+0.7}_{-0.3} \pm 0.4) MeV$, and $m = (2937.9 \pm 1.0^{+1.8}_{-0.4}) MeV/c^2$ and a width $\Gamma = (10 \pm 4 \pm 5) MeV$, for the $\Lambda_c(2880)+$ and $\Lambda_c(2940)+$ respectively. The results from Belle and Babar are in very good agreement. Belle has also performed an angular analysis of the $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{++/0}\pi^{0/+}$ and has shown that $J \geq 5/2$ is favored.

Belle [34] has observed two new Ξ_c states decaying into $\Lambda_c^+\pi^-\pi^+$, the $\Xi_c(2980)^+$ with $m = (2978.5 \pm 2.1 \pm 2.0) MeV/c^2$ and $\Gamma = (43.5 \pm 7.5 \pm 7.0) MeV$, and the $\Xi_c(3077)^+$ with $m = (3076.7 \pm 0.9 \pm 0.5) MeV/c^2$ and $\Gamma = (6.2 \pm 1.2 \pm 0.8) MeV$. Babar [35] has confirmed these observations and measured the following parameters $m = (2967.1 \pm 1.9 \pm 1.0) MeV/c^2$ and $\Gamma = (23.6 \pm 2.8 \pm 1.3) MeV$ and $m = (3076.41 \pm 0.69 \pm 0.21) MeV/c^2$ and $\Gamma = (6.2 \pm 1.6 \pm 0.5) MeV$, respectively for the $\Xi_c(2980)^+$ and the $\Xi_c(3077)^+$.

The electromagnetic decay $\Xi'_c \to \Xi_c\gamma$ has been measured by Babar [36]. It is a confirmation of the Cleo observation. Contributions from B decays and from continuum are separated with the use of a cut on the Ξ_c momentum measured in the center of mass frame. Branching fractions measured from production in B decays are $B(B \to \Xi_c'^+X) \times B(\Xi_c^+ \to \Xi^-\pi^+\pi^-) = (1.69 \pm 0.17 \pm 0.10)10^{-4}$ and $B(B \to \Xi_c'^0) \times B(\Xi_c^0 \to \Xi^-\pi^+) = (0.67 \pm 0.07 \pm 0.03)10^{-4}$. For production from the continuum the cross sections are found to be $\sigma(e^+e^- \to \Xi_c'^+X) \times B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = 141 \pm 24(exp) \pm 19(model)$fb and $\sigma(e^+e^- \to \Xi_c'^0X) \times B(\Xi_c^0 \to \Xi^-\pi^+) = 70 \pm 11(exp) \pm 6(model)$fb. The helicity angle distributions of Ξ'_c decays are found to be consistent with $J = \frac{1}{2}$.

Using a large Λ_c sample, Babar [37] has studied $\Lambda_c\bar{\Lambda}_c$ correlation production $e^+e^- \to \Lambda_c\bar{\Lambda}_cX$, where the $\Lambda_c \to$ is reconstructed in the $pK^-\pi+$ and pK^s decay modes and the $\bar{\Lambda}_c$ in the corresponding charge-conjugate modes. The number of observed events is roughly 4.2 times the number of expected events with respect to models with at leasts four baryons in the final state.

These events show very few additional baryons but multiple mesons, indicating a previously unobserved type of $e^+e^- \to q\bar{q}$ events.

Conclusion

There have been a lot of activity in charm and charmonium spectroscopy at the B-factories during the last few years. Some of the newly discovered states match theoritical expectations, but most of them, such as the X(3872) and the Y(4260) are still to be understood.

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