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Hadron spectroscopy at BABAR

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Abstract. The high integrated luminosity collected by the BABAR detector at the SLAC PEP-II e^+e^- B-Factory offers an excellent opportunity for the study of heavy-quark spectroscopy. A selection of the most recent results reported by BABAR will be presented, focussing on recently observed states with both open- and hidden-charm content.

PACS. 13.25.Gv Decays of J/ψ, Υ, and other quarkonia – 13.25.Ft Decays of charmed mesons – 13.66.Bc Hadron production in e^-e^+ interactions

1 Introduction

The B-Factory experiments offer an excellent opportunity for hadronic-spectroscopy studies. In fact, they accumulated huge data samples, more than $390\,\mathrm{fb}^{-1}$ in the case of BABAR, and allow to exploit various hadron-production mechanisms: not only B-meson decays, but also $e^+e^- \rightarrow q\bar{q}$ events ($q = u, d, s, c$), events with initial state radiation (ISR) and $\gamma\gamma$ collisions, for which all a high efficiency is maintained.

2 States with $c\bar{s}$ content

Recently BABAR [1] and CLEO [2] discovered two narrow mesons with $c\bar{s}$ content in $e^+e^- \rightarrow c\bar{c}$ events, around a mass of $2320\,\mathrm{MeV}/c^2$ ($D^*_{sJ}(2320)^+$ [3]) and $2460\,\mathrm{MeV}/c^2$ ($D_{sJ}(2460)^+$), respectively, later confirmed by Belle [4]. They could be the missing 0^+ and 1^+ levels of the D_s-meson spectrum, but their masses are quite below the expectations, namely they were expected to lie above the DK and D^*K thresholds, thus being very wide. In addition, they have been discovered in the $D_s^{(*)+}\pi^0$ decay modes, that violate isospin (I) conservation for D_s states. Less conventional interpretations have been proposed for these two particles, including tetraquarks [5] and molecular states [6]. BABAR carried on an extensive program aimed at improving the knowledge of their properties. Precision measurements of the masses of the two states have been reported, $(2319.6 \pm 0.2 \pm 1.4)$ and $(2460.2 \pm 0.2 \pm 0.8)\,\mathrm{MeV}/c^2$, as well as upper limits on the total widths of 3.8 and $3.5\,\mathrm{MeV}/c^2$, at the 95% C.L., respectively [7]. The decay channels $D_s^+\pi^0$, $D_s^+\gamma$, $D_s^+\pi^0\gamma$, $D_s^+\pi^+\pi^-$ and $D_s^+\pi^0\pi^0$ have been studied. The $D^*_{sJ}(2320)^+$ has only been observed to decay to $D_s^+\pi^0$, whereas the $D_{sJ}(2460)^+$ has been observed in the $D_s^+\gamma$, $D_s^+\pi^0\gamma$ and $D_s^+\pi^+\pi^-$ decay modes. No sign of $D_{sJ}(2460)^+$ has been observed in the $D_s^+\pi^0\pi^0$ final state: this is suggestive that the $\pi^+\pi^-$ pair in the $D_s^+\pi^+\pi^-$ final state has isospin 1, hence that isospin is not conserved in the $D_s^+\pi\pi$ decay. Also, isospin partners of $D^*_{sJ}(2317)^+$ with 0 or 2 charge, foreseen in molecular models, have been sought for in the $D_s^+\pi^\pm$ decay modes, but no hint of any signal has been reported, implying null isospin.

Also, B-meson decays to $D_{sJ}(2460)^+$ have been studied [8]. By fully reconstructing one of the two B-mesons produced in the process $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$, and a $D^{(*)}$-meson in its recoil, a clear signal of $D_{sJ}(2460)^+$ was reported in the missing-mass spectrum (fig. 1). Using previously measured products of branching fractions $\mathcal{B}(B \rightarrow D_{sJ}(2460)^+D^{(*)}) \times \mathcal{B}(D_{sJ}(2460)^+ \rightarrow f)$ [9], this technique allowed to derive absolute measurements of the branching fractions for the $D_{sJ}(2460)^+$ decay channels f: $\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+\pi^+\pi^-) = (0.04 \pm 0.01)$, $\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+\gamma) = (0.16 \pm 0.04 \pm 0.03)$, $\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^{*+}\pi^0) = (0.56 \pm 0.13 \pm 0.09)$: these add up to $76 \pm 17\%$ of the total $D_{sJ}(2460)^+$ decay width. In addition, the helicity distribution of $D_{sJ}(2460)^+ \rightarrow D_s^+\gamma$ in fully reconstructed $B \rightarrow D_{sJ}D$ decays favours the hypothesis that the $D_{sJ}(2460)^+$ angular momentum J be 1 [9].

Summing up all this information, one can conclude that $D^*_{sJ}(2320)^+$ has been established to have $I = 0$, $J = 0$, positive parity, and to mostly decay to $D_s^+\pi^0$, while $D_{sJ}(2460)^+$ is favoured to have $I = 0$, $J = 1$ and positive parity. In addition, its absolute branching fractions have been measured. These states indeed appear to

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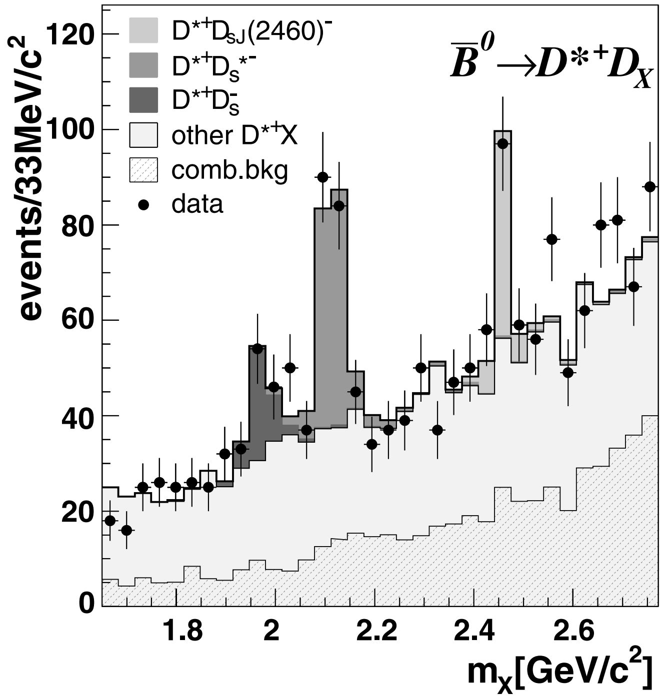

Fig. 1. Distribution of the missing mass (points) in events with a fully reconstructed $\bar{B}^0$- and D^{*+}-meson, overlaid to the result of a fit to a signal plus background hypothesis (histogram).

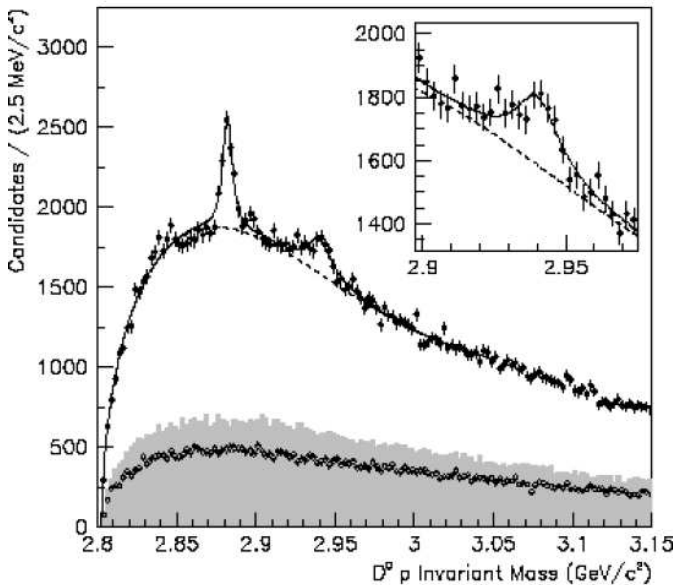

Fig. 2. D^0p invariant-mass distribution (solid points) overlaid to the result of a fit to a background component plus a $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ signal hypothesis (solid curve). The shaded histogram represents the background from D^0 mass sidebands, while the open points represent the invariant mass of wrong-sign $\bar{D}^0p$ pairs.

be consistent with the missing 0^+ and 1^+ levels of the D_s spectrum, although the low masses remain to be better understood.

3 A new charm baryon

The study of the invariant-mass spectrum of D^0-proton pairs in $e^+e^- \to c\bar{c}$ events (fig. 2) led to the observation of a new baryon with mass $(2939.8 \pm 1.3 \pm 1.0)\,\mathrm{MeV}/c^2$ and width $(17.5 \pm 5.2 \pm 5.9)\,\mathrm{MeV}/c^2$ [10]. Also, the observation of the $\Lambda_c(2880)^+ \to D^0p$ decay was reported, allowing the first measurement of its width ($5.8 \pm 1.5 \pm 1.1\,\mathrm{MeV}/c^2$): previously, this state was only observed to decay to $\Lambda_c\pi^+\pi^-$. These represent the first observations of a c-baryon–to–c-meson decay. The study of the D^+p invariant-mass spectrum did not reveal any charged partners of the two states, confirming the assignment of both to the Λ_c family.

4 States with $c\bar{c}$ content

The spectrum of $c\bar{c}$ bound states is well known below the open-charm threshold, and there good agreement is found with the potential model expectations. More charmonium states with $J^{PC} = 1^{--}$ are known above the open-charm threshold from the R scans [11]. On the other hand, many levels are still to be discovered. In addition, QCD predicts a richer spectroscopy: hybrids ($c\bar{c}g$), $D^{(*)}\bar{D}^{(*)}$ molecules, tetraquarks; the recent discovery at the B-Factories of many states with properties not well fitting within the potential model for conventional $c\bar{c}$ states, like $X(3870)$ [12] and $Y(4260)$ [13], led to a new interest in this spectroscopy. BABAR undertook a rich program of studies of both B decays and ISR events to try and improve the knowledge of these states.

The production of $X(3870)$ in both charged and neutral B decays to $J/\psi\pi^+\pi^-K$ was studied [14]. If $X(3870)$ is a conventional charmonium state, a similar production ratio r_{0+} from B^0 and B^+ is expected; if, on the contrary, it is a molecule, several models predict that the B^0 production be suppressed [15]. Also, if it were a tetraquark, it is foreseen that the states produced by B^0 and B^+ be not the same, and have a mass difference of about $7\,\mathrm{MeV}/c^2$ [5]. A clear signal was observed in B^+ decays, and a 2.5 standard-deviations excess in B^0 decays; r_{0+} was measured to be $0.50 \pm 0.30 \pm 0.05$. The mass difference was measured to be $(2.7 \pm 1.3 \pm 0.2)\,\mathrm{MeV}/c^2$. The method appears therefore interesting, however more data are needed to distinguish between the various models.

Charged partners of $X(3870)$, foreseen in molecular models, were sought for in B^0 and B^- decays to $J/\psi\pi^-\pi^0K$: no signal was reported, ruling out the isovector hypothesis for $X(3870)$ at the 10^{-4} C.L. [16].

The observation of the $J/\psi\gamma$ decay of $X(3870)$ was reported in the $B^+ \to J/\psi\gamma K^+$ process [17]. This decay mode implies positive charge parity (C) for $X(3870)$, and consequently that the $\pi^+\pi^-$ pair in the $J/\psi\pi^+\pi^-$ mode has isospin 1, hence that the decay to $J/\psi\pi^+\pi^-$ violates isospin conservation, confirming BELLE [18] and CDF [19] results. The ratio of the branching fraction for $J/\psi\gamma$ to $J/\psi\pi^+\pi^-$ was measured to be 0.34 ± 0.14.

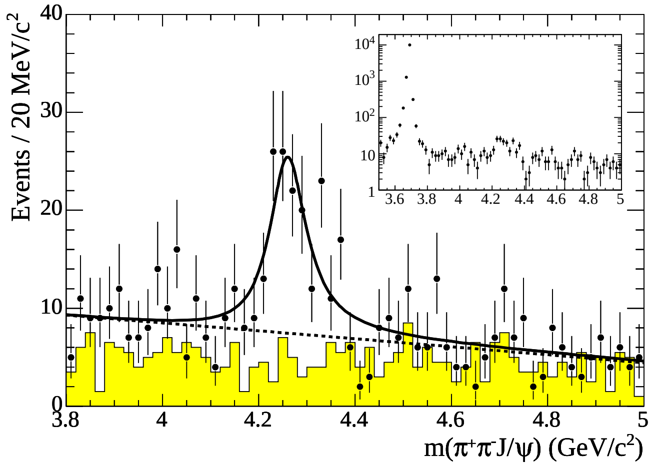

Fig. 3. The $J/\psi\pi^+\pi^-$ invariant-mass spectrum in ISR events in the 3.8–5.0 GeV/c^2 range and in a wider range (inset). The result of a fit to a single-resonance hypothesis plus background (solid curve) is superimposed to the data points; the shaded histogram represents the scaled data from J/ψ mass sidebands.

A recoil technique similar to the one described above was also used for the $X(3870)$, studying the missing mass recoiling against a K^+. An upper limit was set for $B^+ \to X(3870)K^+$ of 3.2×10^{-4}, at the 90% C.L., allowing to derive $\mathcal{B}(X(3870) \to J/\psi\pi^+\pi^-) > 4.2\%$ [20].

The study of $J/\psi\pi^+\pi^-$ states in ISR events did not reveal any signal for $X(3870)$, consistent with the $C = +$ assignement, however a structure ($Y(4260)$) was observed at higher masses (fig. 3): if interpreted as a single resonance, this has a mass of $(4259 \pm 8^{+2}_{-6})\,\mathrm{MeV}/c^2$ and a width of $(88 \pm 23^{+6}_{-4})\,\mathrm{MeV}/c^2$ [13]. Being well above the open-charm threshold and wide, its partial width to $J/\psi\pi^+\pi^-$ is expected to be very small in the conventional charmonium scenario, so alternative interpretations were proposed [21]. The search for other decay modes of $Y(4260)$ in ISR events led to negative results: no signals were reported for the $\phi\pi^+\pi^-$ [22], $p\bar{p}$ [23], $D\bar{D}$ [24] modes. A hint of a possible $Y(4260)$ signal was reported in $B^+ \to J/\psi\pi^+\pi^-K^+$ decays, leading to a branching fraction product $\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$ [14].

Summing up all this information and the information reported by other experiments, mainly by BELLE, but also by CLEO, CDF and D0, it is apparent that $X(3870)$ and $Y(4260)$ are not easy to accommodate within the conventional charmonium picture. The $X(3870)$ is near the DD^* threshold, but it is very narrow, it decays to $J/\psi\pi^+\pi^-$ with isospin violation, and it was also observed to decay to $J/\psi\pi^+\pi^-\pi^0$, $D^0\bar{D}^{*0}$ and $J/\psi\gamma$. The $J^{PC} = 1^{++}$ and $I = 0$ quantum number assignments are favoured: the χ'_{c1} charmonium state would be consistent with this, but the mass would be too small. The $Y(4260)$ was only observed so far in the $J/\psi\pi\pi$ mode; since it was seen in ISR, it has $J^{PC} = 1^{--}$, however it was not observed in the R scans in the past, in contrast with the other 1^{--} charmonium states.

5 Conclusion

BABAR is greatly contributing to hadron spectroscopy. Significant progresses have been attained towards a better understanding of states with $c\bar{s}$ and $c\bar{c}$ content, including precision measurements of masses and widths, as well as quantum numbers of recently discovered states, and more decay modes and production mechanisms have been investigated. More data are being accumulated and new results are on the way in this field of renewed interest.

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