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New charmonium and charm states at *BABAR*

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Abstract. We review the latest *BABAR* results on charm spectroscopy focussing on recently observed states with both hidden and open charm content.

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INTRODUCTION

Charmonium and charm studies at B factories have led to a series of new states that are challenging conventional heavy-flavour spectroscopy. The *BABAR*/PeP-II B Factory at SLAC has undertaken a number of studies to look for additional states and understand the nature of the recently discovered ones.

Here, we review the latest experimental results on meson and baryon spectroscopy focussing on recently observed states with both hidden and open charm content.

CHARMONIUM-LIKE STATES

Five new states have been discovered recently at B factories above open-charm threshold with properties not well-fitting quark model and Lattice QCD calculations for $c\bar{c}$ bound states. Among these charmonium-like states, particularly puzzling are two resonances decaying to $J/\psi\ \pi^+\ \pi^-$: $X(3872)$, first observed by Belle [1] in $B^+ \to K^+ J/\psi \pi^+ \pi^-$, and $Y(4260)$, discovered by *BABAR* [2] in e^+e^- events with initial state radiation (ISR), $e^+e^- \to (\gamma) J/\psi \pi^+ \pi^-$.

$X(3872)$

The existence of $X(3872)$ is well established. Soon after the discovery by Belle [1] in 2003, this state was confirmed by CDF [3], D0 [4], and *BABAR* [5]. Other decay modes of the $X(3872)$ have also been observed. Quantum numbers are not firmly established yet, though angular distribution studies [6] in the $J/\psi\ \pi^+\ \pi^-$ decay channel favour $J^{PC} = 1^{++}$.

Recently, both Belle and *BABAR*, have measured the radiative decay $X(3872) \to J/\psi \gamma$ [7, 8] with an average branching ratio of (19±7)% relative to the $X(3872) \to J/\psi \pi^+ \pi^-$ decay mode. The observation of this mode firmly establishes that the $X(3872)$ has even C-parity. The identification of $X(3872)$ with χ'_{c1}, the only remaining possibility

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for a conventional state with $J^{PC} = 1^{++}$, is not well consistent with the measured mass $(3871.2 \pm 0.6)\,\mathrm{MeV}/c^2$. Hence, mainly non-conventional interpretations remain, in particular that of a loose-bound $D^0\bar{D}^{*0}$molecule or a tetra-quark, which are currently viewed as the most likely explanations [9].

$Y(4260)$

The production mechanism, through single photon annihilation in ISR events, requires that $Y(4260)$ is vector state with $J^{PC} = 1^{--}$. The most exceptional feature for this state is its relatively large coupling to $J/\psi\pi\pi$ compared to open charm decays. *BABAR* has searched for the $Y(4260)$ decay to a neutral or charged pair of D mesons [10]. No signal has been found and an upper limit has been set: $\frac{\mathscr{B}(Y(4260)\to D\bar{D})}{Y(4260)\to J/\psi\,\pi^+\pi^-} < 7.6$ at 95% C.L.. This is another indication that $Y(4260)$ is not a conventional vector charmonium state. Currently, the most favoured explanation, consistent with all observations, is that of a $c\bar{c}g$ hybrid [9].

BABAR has also searched for $Y(4260) \to \psi(2S)\pi^+\pi^-$ [11] in ISR events and observed a structure in the $\psi(2S)$ π^+ π^- invariant mass spectrum at slightly higher mass, near $4.32\,\mathrm{GeV}/c^2$. A fit with a single resonance well describes the spectrum in the region below $5.7\,\mathrm{GeV}/c^2$. The fitted values of the Breit-Wigner parameters are a mass of $(4324 \pm 24)\,\mathrm{MeV}/c^2$ and a width of $(172 \pm 33)\,\mathrm{MeV}$, where the errors are statistical only. The goodness-of-fit, measured by a χ^2, deteriorates significantly if mass and width are fixed to the *BABAR* values for $Y(4260)$, hence the hypothesis has been made that the observed structure is not due to the $Y(4260)$ but indicates the presence of another new state. However, no definitive conclusions can be drawn from the present data and an independent confirmation by other experiments is eagerly awaited.

A NEW CHARMED-STRANGE MESON

Spectroscopy of $c\bar{s}$ states has also generated a lot of interest recently thanks to the discovery of $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ by the *BABAR* [12] and CLEO [13] collaborations. In particular, the identification of $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ with two $c\bar{s}$ P-wave states, $J^P = 0^+$ and 1^+, has been very much debated, since these states were predicted at higher mass and to decay broadly to a charm meson and a kaon.

News in this sector comes from the studies of the inclusive DK production in e^+e^- events by *BABAR* [14], which show the presence of a new broad resonance in the D^0K^+ and in the $D^+K^0_s$ invariant mass spectra. Several checks have been made to rule out fake signals due to possible reflections. No signal is seen in simulated events and studies of the D mass sidebands do not show any extra structure. Therefore, this is a genuine signal of a new state with a mass of $(2856.6 \pm 1.5 \pm 5.0)\,\mathrm{MeV}/c^2$ and a width of $(48 \pm 7 \pm 10)\,\mathrm{MeV}$, as determined by a combined fit to the D^0K^+ and $D^+K^0_s$ mass spectra. The spin-parity of this state has not yet been established, but theoretical speculations indicate that it could be a $J^P = 3^-$ [15] D-wave state or a radial excitation of the $D^*_{sJ}(2317)^+$ [16].

A broad peak is also observed just below $2.7\,\mathrm{GeV}/c^2$. This bump can be well described by an additional Breit-Wigner in the fit model with a mass of $(2688\pm4\pm3)\,\mathrm{MeV}/c^2$ and a width of $(112\pm7\pm36)\,\mathrm{MeV}/c^2$. However, in this case, a hint of a structure could be seen in the same mass region when using candidates from a D^0 mass sideband. Therefore *BABAR* is not able to establish whether this is a new state. We note that this bump could coincide with a D^0K^+ resonance reported by Belle [17] in $B^+ \to D^0\bar{D}^0K^+$ at a mass of about 2715 MeV/c^2.

CHARMED BARYONS

The particle spectrum of baryons with a single charm quark is also expected to have a rich structure of radial and orbitally-excited states. All nine $J^P = \frac{1}{2}^+$ with $L=0$ are well-known. Here we report the observation of the last of the six $J^P = \frac{3}{2}^+$ states without internal orbital angular momentum, the Ω_c^*, and of three new $L=1$ charmed baryons, recently observed by *BABAR*.

Ω_c^*

The Ω_c^* has been observed by *BABAR* [18] in the radiative decay $\Omega_c^* \to \Omega_c^0\gamma$. The mass difference between Ω_c^* and Ω_c^0 is determined to be $(70.8\pm1.0\pm1.1)\,\mathrm{MeV}/c^2$, in agreement with theoretical calculations [19]. The ratio of the production cross-section of $e^+e^- \to \Omega_c^*X$ relative to $e^+e^- \to \Omega_c^0X$, where X denotes the rest of the event, is measured to be $1.01\pm0.23\pm0.11$.

$\Lambda_c(2940)^+$

The study of the invariant mass spectrum of D^0-proton pairs in $e^+e^- \to c\bar{c}$ events has led to the observation of a new charmed baryon with mass $(2939.8\pm1.3\pm1.0)\,\mathrm{MeV}/c^2$ and width $(17.5\pm5.2\pm5.9)\,\mathrm{MeV}/c^2$ [20]. A second larger peak in the D^0p mass spectrum, at a mass of $(2881.9\pm0.1\pm0.5)\,\mathrm{MeV}/c^2$ and a width of $(5.8\pm1.5\pm1.1)\,\mathrm{MeV}$ is identified as the $\Lambda_c(2880)^+$, previously discovered in decays to $\Lambda_c^+\pi^+\pi^-$. These are the first charmed baryons observed to decay to a charmed meson and a charmless baryon. Because of the absence of a charge partner in the D^+p mass spectrum, the new state is identified as the isospin scalar $\Lambda_c(2940)^+$. Its spin-parity has yet to be determined.

$\Xi_c(2980)^+$ and $\Xi_c(3077)^+$

BABAR [21] has also confirmed the discovery of two new Ξ_c states by Belle [22]: $\Xi_c(2980)^+$ and $\Xi_c(3077)^+$, decaying into $\Lambda_c^+K^-\pi^+$. The masses and widths are determined in a 2D fit to the $\Lambda_c^+K^-\pi^+$ and $\Lambda_c^+\pi^+$ mass spectra. Results are in general consistent with Belle's measurements, except for the mass and width of $\Xi_c(2980)^+$,

$(2967 \pm 1.9 \pm 1.0)\,\mathrm{MeV}/c^2$ and $(23.6 \pm 2.8 \pm 1.3)\,\mathrm{MeV}/c^2$ respectively, which are both significantly lower than Belle's values [22]. The discrepancy is probably due to the different signal model, in particular to the inclusion of a mass-dependent phase-space factor in the *BABAR* fit, which affects mainly the shape near threshold. The second dimension in the fit allows *BABAR* to determine that quasi-two body decays via a Σ_c^{++} are dominant for $\Xi_c(3077)^+$ and represent about 50% of $\Xi_c(2980)^+$ decays.

SUMMARY

A surge of new states with charm content have been recently observed at *BABAR*. In the hidden charm sector, the new available results on $X(3872)$ and $Y(4260)$ support the hypothesis that these are not conventional charmonium states. In the open charm sector new insights on the understanding of the hadron spectra come from the discovery of a new charmed-strange meson, $D_{sJ}^*(2860)$, and of several charmed baryons. Other sightings, in particular the structure at $\sim 4.32\,\mathrm{GeV}/c^2$ in the $\psi(2S)\pi^+\pi^-$ ISR spectrum, are also very interesting and call for confirmation.

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