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CHARM SPECTROSCOPY AT *BABAR*

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Abstract

We present a mini-review on charm spectroscopy at the *BABAR* experiment. We first report on the $c\bar{s}$ meson spectrum, and present precise measurements of the $D_{s1}(2536)$ meson as well as the properties of the many new states discovered since 2003 ($D^*_{s0}(2317)$, $D_{s1}(2460)$, $D^*_{sJ}(2860)$, and $D_{sJ}(2700)$ mesons). We then discuss about charmed baryons observed recently in the *BABAR* experiment: Ω_c^0 and Ω_c^{*0} css baryons, $\Lambda_c(2940)^+$ udc baryon and the Ξ_c usc/dsc baryons.

1 Introduction

Observations of a long list of new meson and baryon resonances have been recently reported by the *BABAR*, Belle and CLEO experiments. We present here the new resonances observed in the $c\bar{s}$ and charmed baryon sectors by the *BABAR* experiment.

For BaBar Collaboration

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In this short review, we do not present results on $c\bar{u}$ and $c\bar{d}$ resonances (D, D^*, D^{**} mesons) and on $c\bar{c}$ states (charmonium or charmonium-like state).

Analyzes presented here were performed using data collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector [1], located at the PEP-II asymmetric energy e^+e^- collider. From 1999 to 2007, the *BABAR* experiment recorded a luminosity of 432 fb^{-1} at the $\Upsilon(4S)$ peak and 45 fb^{-1} at 40 MeV below the peak. This corresponds to about 475.10^6 $B\bar{B}$ pairs and 620.10^6 $c\bar{c}$ pairs. The analyzes presented here use only a subset of the total recorded luminosity.

2 $c\bar{s}$ mesons

Before 2003, only four $c\bar{s}$ mesons were known: two S-wave mesons, D_s ($J^P = 0^-$) and D_s^* (1^-), and two P-wave mesons, $D_{s1}(2536)$ (1^+) and $D_{s2}(2573)$ (2^+). The masses predicted by the potential model [2] were in good agreement with the measured masses. The potential model predicted also two other broad states (width of a few hundred of MeV) at masses between 2.4 and 2.6 GeV/c^2.

2.1 $D_{s1}(2536)$ meson

With the discovery of additional $c\bar{s}$ mesons, a comprehensive knowledge of all known D_s mesons is mandatory. As of 2006, the properties of the $D_{s1}(2536)$ meson were not perfectly known: the width was determined to be less than 2.3 MeV at 90% confidence level, and the quantum numbers were only inferred.

In Ref. [3], a high precision measurement of the mass and of the width was performed, using events in the $c\bar{c}$ continuum. Reconstructing inclusively the decay $D_{s1}(2536) \to D^{*+}K^0_S$, with $D^{*+} \to D^0\pi^+$ and D^0 decaying either to $K^-\pi^+$ or to $K^-\pi^+\pi^-\pi^+$, one obtain a mass of $(2534.85 \pm 0.02 \pm 0.40)$ MeV/c^2 (where the first error is statistical and the second is systematic). The error on the mass is dominated by the uncertainty on the D^{*+} mass. Furthermore, the width was measured at a value of $(1.03 \pm 0.05 \pm 0.12)$ MeV. This is the first time that a direct measurement of the width is given, rather than just an upper limit.

Additionally, in another analysis [4], the $D_{s1}(2536)$ meson was reconstructed exclusively in B decays, with $B \to D^{(*)}D_{s1}(2536)$ (8 modes in total) followed by $D_{s1}(2536) \to D^*K$. A total of 182 ± 19 events is seen, which gives an observation at the 12σ significance level (where σ is the 68% C.L. standard deviation). With this method, a mass of $(2534.78 \pm 0.31 \pm 0.40)$ MeV/c^2 is obtained, in good agreement with the inclusive measurement. The exclusive reconstruction allows to determine the J^P quantum number: fits to the helicity distribution in the data favor the quantum number $J = 1$ while $J = 2$ is disfavored. More statistics is needed to conclude definitely and determine the parity P.

2.2 $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons

In 2003, two new resonances were discovered by the *BABAR* and CLEO experiments: the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons [5]. These two resonances are very narrow, and have masses well below what was predicted by the potential model (the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons were predicted to lie above the DK and D^*K threshold, respectively, but have been observed below these thresholds). These states are very well known experimentally: masses are measured with an error below 2 MeV/c^2, 95% confidence level upper limits on widths are about 4 MeV ; J^P quantum numbers (0^+ and 1^+ for $D_{s0}^*(2317)$ and $D_{s1}(2460)$ respectively), decay modes and branching fractions are also well measured. Despite a good knowledge of these states, their theoretical interpretation is still unclear. One obvious possibility is to identify these two resonances with the 0^+ and 1^+ $c\bar{s}$ states, although it is difficult to fit these resonances within the potential model. Other interpretations have been proposed: four quark states, DK molecules or $D\pi$ atoms [6].

2.3 $D_{sJ}^*(2860)$ meson

The $D_{sJ}^*(2860)$ resonance was discovered by *BABAR* in 2006 [7], looking in the $c\bar{c}$ continuum: $e^+e^- \to D^0K^+X$ and $e^+e^- \to D^+K_s^0X$, where we consider the decays $D^0 \to K^-\pi^+, K^-\pi^+\pi^0$ and $D^+ \to K^-\pi^+\pi^+$ and where X could be anything. A clear peak is observed in the DK invariant mass for the sum of these 3 modes, with a mass of $(2856.6 \pm 1.5 \pm 5.0)$ MeV/c^2 and a width of $(47 \pm 7 \pm 10)$ MeV. This signal is seen with a statistical significance above 8σ. Although this resonance is observed with a high significance, no other experiments have yet confirmed this state. Given that this resonance decays to two pseudoscalars, the J^P quantum number should be 0^+, 1^-, 2^+, etc. Different interpretations have been proposed, inside the $c\bar{s}$ scheme: this state could be a radial excitation of the $D_{s0}^*(2317)$, but other possibilities are not ruled out [8].

2.4 $D_{sJ}(2700)$ meson

In the same analysis, *BABAR* reported a broad enhancement, named $X(2690)$, at a mass of $(2688 \pm 4 \pm 3)$ MeV/c^2 and a width of $(112 \pm 7 \pm 36)$ MeV. A new state, the $D_{sJ}(2700)$, was reported independently by Belle at a similar mass, with a J^P quantum number equal to 1^-, looking at $B^+ \to \bar{D}^0 D^0 K^+$ events [9]. Since the $X(2690)$ and $D_{sJ}(2700)$ mesons have the same decay modes and that the mass and width are consistent with each other, it is reasonable to think that they are indeed the same state.

BABAR performed an exclusive analysis [9], looking at events where B decays to $\bar{D}^{(*)} D^{(*)} K$. Thanks to the many final states studied, this analysis has the advantage to be able to look at four $D^0 K^+$ invariant mass distributions as well as four $D^+ K_s^0$ invariant mass distributions. Adding these final states together, a clear resonant enhancement is seen around a mass of 2700 MeV/c^2. Furthermore, adding the four $D^{*0} K^+$ and four $D^{*+} K_s^0$ invariant mass distributions together, a similar enhancement is observed around a mass of 2700 MeV/c^2. No precise measurement was given by this preliminary analysis yet.

The potential model predicts the 2^3S_1 $c\bar{s}$ state at a mass of 2720 MeV/c^2. Also, from chiral symmetry considerations, a $1^+ - 1^-$ doublet of states has been predicted. If the 1^+ state is identified as the $D_{s1}(2536)$, the mass predicted for the 1^- state is (2721 ± 10) MeV/c^2 [10].

3 Charmed baryons

The production and decay of singly-charmed baryons are largely unexplored and provide an interesting environment to study the dynamics of quark-gluon interactions. All nine ground states with $J^P = 1/2^+$ and all six ground states with $J^P = 3/2^+$ are now observed (the last missing state, Ω_c^{*0}, was discovered by *BABAR* in 2006). Several orbitally excited states have already been seen as well. The spin and parity of each of these excited single-charm baryons are assigned based on a comparison of the measured masses and natural widths with predictions of theoretical models.

3.1 Ω_c^0 and Ω_c^{*0} baryons

The Ω_c^0 baryon, a css state with $J^P = 1/2^+$, was observed by *BABAR* [11] decaying to four hadronic modes: $\Omega_c^0 \to \Omega^- \pi^+$ (with a significance of 18σ), $\Omega_c^0 \to \Omega^- \pi^+ \pi^0$ (5.1σ), $\Omega_c^0 \to \Omega^- \pi^+ \pi^+ \pi^-$ (4.2σ) and $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$ (4.3σ). The ratios of branching fractions were measured, significantly improving upon the previous values. The p^* spectrum of Ω_c^0 was also measured in order to study the production rates in both $c\bar{c}$ and $B\bar{B}$ events, using only the $\Omega^- \pi^+$ final state. This analysis find comparable production rates of Ω_c^0 baryons from the continuum and from B meson decays. This is the first observation of this baryon in B decays.

Recently, *BABAR* discovered [12] the css ground state with $J^P = 3/2^+$, the Ω_c^{*0} baryon. This baryon was observed with a significance of 5.2σ in the decay to $\Omega_c^0 \gamma$, combining the four decay modes of the Ω_c^0 cited in the previous paragraph. The difference of mass between Ω_c^{*0} and Ω_c^0 was measured to be $(70.8 \pm 1.0 \pm 1.1)$ MeV/c^2. A non-relativistic QCD effective field theory calculation predicts the mass difference to be in the range 50-73 MeV/c^2, while a lattice calculation gives a mass difference equal to (94 ± 10) MeV/c^2 [13].

The ratio of inclusive production cross-section was determined to be

$$\frac{\sigma(e^+e^- \to \Omega_c^{*0} X, x_p(\Omega_c^{*0}) > 0.5)}{\sigma(e^+e^- \to \Omega_c^0 X, x_p(\Omega_c^0) > 0.5)} = 1.01 \pm 0.23 \pm 0.11, \qquad (1)$$

where the scaled momentum $x_p = p^*/p^*_{\rm max}$ of the Ω_c^{*0} (Ω_c^0) is required to be greater than 0.5 in the numerator (denominator) cross-section.

3.2 $\Lambda_c(2940)^+$ baryon

A search for charmed baryons decaying to $D^0 p$ was performed [14] and revealed two states: the $\Lambda_c(2880)^+$ baryon and a previously unobserved state, the $\Lambda_c(2940)^+$. This is the first observation of charmed baryons decaying to a D meson and a light baryon.

The $\Lambda_c(2880)^+$ baryon was previously observed [15] by the CLEO experiment in the $\Lambda_c \pi^+ \pi^-$ decay mode, with a mass of (2880.9 ± 2.3) MeV/c^2 and a width less than 8 MeV at 90% confidence level. Using *BABAR* data in the $D^0 p$ channel leads to much more precise values, in particular with the first measurement of the width of the $\Lambda_c(2880)^+$: $m = (2881.9 \pm 0.1 \pm 0.5)$ MeV/c^2

and $\Gamma = (5.8 \pm 1.5 \pm 1.1)$ MeV. The existence of the decay $D^0 p$ rules out various interpretations of this baryon [16].

The new baryon $\Lambda_c(2940)^+$ is observed with a significance above 7σ, with a mass of $(2939.8 \pm 1.3 \pm 1.0)$ MeV/c^2 and an intrinsic width of $(17.5 \pm 5.2 \pm 5.9)$ MeV. This new state could be interpreted as a udc baryon. To determine if this new state belongs to an isotriplet (analogous to Σ_c^0 and Σ_c^{++}), a search for doubly-charged partner was performed, looking at the decay mode $D^+ p$. No signal corresponding to either the $\Lambda_c(2880)^+$ or $\Lambda_c(2940)^+$ baryon was observed, which shows that both states are isoscalar.

3.3 $\Xi_c(2980)^+$, $\Xi_c(3077)^{+/0}$, $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ baryons

The *BABAR* experiment searched [17] for the excited charm-strange baryons $\Xi_c(2980)^+$ and $\Xi_c(3077)^{+/0}$, discovered previously by the Belle collaboration [18]. *BABAR* confirms the states $\Xi_c(2980)^+$, $\Xi_c(3077)^{+/0}$, looking at the $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K_S^0 \pi^-$ final states, with $\Lambda_c^+ \to pK^-\pi^+$, pK_S^0, $pK_S^0\pi^-\pi^+$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^-\pi^+$. The $\Xi_c(2980)^+$ baryon is observed at a mass of $(2969.3 \pm 2.2 \pm 1.7)$ MeV/c^2 with a width of $(27 \pm 8 \pm 2)$ MeV. The $\Xi_c(3077)^+$ is seen at a mass of $(3077.0 \pm 0.4 \pm 0.2)$ MeV/c^2 with an intrinsic width of $(5.5 \pm 1.3 \pm 0.6)$ MeV. *BABAR* confirmed also the $\Xi_c(3077)^0$ state at a mass of $(3079.3 \pm 1.1 \pm 0.2)$ MeV/c^2 with a width of $(5.9 \pm 2.3 \pm 1.5)$ MeV. These results are in good agreement with the values given by Belle, except for the $\Xi_c(2980)^+$ baryon where the difference could be explained by the fact that *BABAR* incorporates phase space effect near the threshold and takes into account decays to $\Sigma_c(2455)^{++}K^-$.

In addition to these confirmations, *BABAR* discovered a new baryon, the $\Xi_c(3055)^+$, and found an evidence for the $\Xi_c(3123)^+$ baryon. The $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ signals are observed only in $\Sigma_c(2455)^+K^-$ and $\Sigma_c(2520)^+K^-$ intermediate-resonant decays, respectively. The $\Xi_c(3055)^+$ is seen with a 6.4σ significance, with a mass of $(3054.2 \pm 1.2 \pm 0.5)$ MeV/c^2 and a width of $(17 \pm 6 \pm 11)$ MeV, while the $\Xi_c(3123)^+$ is observed with a 3.6σ significance at a mass of $(3122.9 \pm 1.3 \pm 0.3)$ MeV/c^2 and with a width of $(4.4 \pm 3.4 \pm 1.7)$ MeV.

These baryons have same or similar decay channels as the double-charm baryon, but are identified as single-charm based on the measured masses, natural widths and charges of the members of the isospin doublet. In the current state of knowledge, it is difficult to assign a spin-parity to these baryons. More theoretical and experimental work is needed to clarify the properties of these states.

4 Conclusion

Although no new resonances were discovered in many years, *BABAR* gave an impressive list of new results since 1999. In the $c\bar{s}$ sector, the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ mesons are now very well known experimentally, but no definite interpretation was given theoretically. The $D^*_{sJ}(2860)$ and $D_{sJ}(2700)$ mesons were discovered recently and need more experimental inputs. Many new charmed baryon states were observed by *BABAR*. Thanks to the discovery of the Ω_c^{*0}, all ground states are now established. A lot of excited states have been observed, and probably many of them have yet to be discovered. The production rate, the decay channels and the measured properties (masses, widths) of these excited states will help to understand the internal quark dynamics.

A lot of analyzes are still in progress with the current data set in *BABAR*: more decay modes for the resonances presented here are being investigated. *BABAR* is taking data until the end of 2008, which is the promise of more surprises to arise.

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