Charm and Charmonium Spectroscopy

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Recent experimental results in charm and charmonium spectroscopy are reviewed.

1. INTRODUCTION

The last few years have seen a revival of interest in charm spectroscopy with more than a dozen new states being reported and hundreds of new theoretical investigations being published. The advent of the B-factories [1,2], with their large, charm-rich data samples, has proven crucial to the discovery and investigation of new charm hadron states, but other experiments have confirmed and complemented the B-factory observations. Much interest has been generated by several new states that do not appear to be easily incorporated in the conventional picture of charm and charmonium mesons. Here, the focus is on the latest experimental results in charm spectroscopy and the determination of the nature of the recently discovered states.

2. CHARM MESONS

Before the start of the B-factories, only four charm-strange mesons had been observed: the S-wave states D_s^+ and D_s^{*+} with $J^P = 0^-$ and 1^-, and two P-wave states, $D_{s1}(2536)^+$ and $D_{s2}(2573)^+$, assigned to be 1^+ and 2^+ states. Two additional P-wave states, 0^+ and 1^+, were expected, but predicted by potential models to have a large decay width to a non-strange charm meson and a kaon [3,4]. The observations of two narrow charm-strange mesons below the DK threshold, the $D_{sJ}^*(2317)^+$ [5] and $D_{sJ}(2460)^+$ [6], by the *BABAR* and CLEO collaborations have led to much speculation whether these are the missing 0^+ and 1^+ states or perhaps new types of particles [7].

Several experimental studies of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ have been performed recently to understand their nature. *BABAR* has performed a comprehensive study [8] of the possible decay to a D_s^+ meson and up to two γ or π^0 particles. The $D_{sJ}^*(2317)^+$ is only observed in decay mode $D_s^+\pi^0$, while the $D_{sJ}(2460)^+$ is observed in three modes: $D_s^{*+}\pi^0$, $D_s^+\pi^+\pi^-$ and $D_s^+\gamma$. None of these decays are in disagreement with the assignment of 0^+ and 1^+ for the two states. No other decay modes are observed and limits on the branching ratios are measured [8]. Isospin partners for the $D_{sJ}^*(2317)^+$ are searched for in decays to $D_s^+\pi^\pm$, but none are observed [8].

A separate study by *BABAR* measures the absolute branching fractions of $D_{sJ}(2460)^+$ decays [9]. The analysis selects $B\overline{B}$ events where one B meson is fully reconstructed and used to determine the rest frame of the second B meson. An additional $D^\pm$, D^0 or $D^{*\pm}$ meson from the second B is reconstructed and its recoil mass spectrum studied. A signal is found for $D_{sJ}(2460)^+$ and is used to measure $\mathcal{B}(B \to D^{(*)}D_{sJ}(2460))$. This is combined with previous branching fraction product measurements [10] to obtain absolute branching fractions for $D_{sJ}(2460)^+$ decays. The branching fractions for the three observed modes add up to $(76 \pm 20)\%$, indicating that most of the $D_{sJ}(2460)^+$ decay modes have been observed.

B meson decays have also been used to determine the spin of the two new D_{sJ}^+ states. In the decays $B \to DD_{sJ}^*(2317)^+, D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ [11] and $B \to DD_{sJ}(2460)^+, D_{sJ}(2460)^+ \to D_s^+\gamma$ [11,10], the angular distribution of the D_s^+ meson with respect to the D meson in the D_{sJ}^+ rest frame is measured. This distribution is consistent with flat for the $D^*_{sJ}(2317)^+$ and quadratic for the $D_{sJ}(2460)^+$, establishing that these states have spin 0 and 1, respectively. The $D^*_{sJ}(2317)^+$ therefore has to be a 0^+ state, while for $D_{sJ}(2460)^+$ the possibility of being a 1^- state can be excluded by a similar angular analysis of $D_{sJ}(2460)^+ \to D_s^{*+}\pi^0$ decays. This result indicates that the two D^+_{sJ} states are regular charm-strange mesons, but does not explain why the potential models underestimate their mass.

The SELEX collaboration has reported [12] the possible existence of a new, narrow charm-strange meson decaying to $D_s^+\eta$ and D^0K^+ with a mass of about $2632\,\mathrm{MeV}/c^2$. This state, $D_{sJ}(2632)^+$, is not observed by FOCUS [13], Belle [14] or *BABAR* [15] even though all three have significantly larger reconstructed samples of the nearby $D_{s2}(2573)^+ \to D^0K^+$ decays. This appears to exclude the existence of this state.

Further studies of the D^0K^+ mass spectrum by *BABAR* [16] instead show a peaking structure around $2.86\,\mathrm{GeV}/c^2$. The peak is visible using either $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^0$ decays and the same peak is also seen in the $D^+K^0_S$ mass spectrum. No signal is seen in simulated events or with D^0 mass sideband events. Nor is the peak due to pions misidentified as kaons. A combined fit to the D^0K^+ and $D^+K^0_S$ mass spectrums gives a mass of $2856.6 \pm 1.5 \pm 5.0\,\mathrm{MeV}/c^2$ and a width of $48 \pm 7 \pm 10\,\mathrm{MeV}$. The spin-parity of this state has not yet been established, though it has already been speculated that it could be a $J^P = 3^-$ D-wave state [17] or a radially excitation of the $D^*_{sJ}(2317)^+$ [18].

A broad structure is also observed just below $2.7\,\mathrm{GeV}/c^2$. A fit with an additional Breit-Wigner gives a mass of $2688 \pm 4 \pm 3\,\mathrm{MeV}/c^2$ and a width of $112 \pm 7 \pm 36\,\mathrm{MeV}$ for this structure. However, the fit is not particularly good and there is a hint of structure in the same region when using events from a D^0 mass sideband. *BABAR* is therefore not able to establish whether this is a new state[1].

[1]After this talk was given, Belle reported [19] a possible $D^0\ K^+$ state in $B^+ \to D^0\overline{D}^0K^+$ decays with a mass of $\sim 2715\,\mathrm{MeV}/c^2$. This might be the same state.

3. CHARM BARYONS

Charm baryons with two light quarks provide an even richer particle spectrum than charm mesons. Of the states without internal orbital angular momentum ($L = 0$), all nine $J^P = \frac{1}{2}^+$ states have been known for years [20], while observation of the last of the six $J^P = \frac{3}{2}^+$ states, the Ω^*_c, has been reported very recently [21]. Several possibly orbitally excited charm baryons have already been observed, the latest of which are summarized below.

One new charm baryon has been found [22] to decay to D^0p. A fit to a Breit-Wigner shape folded with experimental resolution yields a mass of $2939.8 \pm 1.3 \pm 1.0\,\mathrm{MeV}/c^2$ and a width of $17.5 \pm 5.2 \pm 5.9\,\mathrm{MeV}$. A second, larger peak is fit with a mass of $2881.9 \pm 0.1 \pm 0.5\,\mathrm{MeV}/c^2$ and a width of $5.8 \pm 1.5 \pm 1.1\,\mathrm{MeV}$ and is identified as the $\Lambda_c(2880)^+$, previously discovered in decays to $\Lambda_c^+\pi^+\pi^-$ decays [23]. These are the first charm baryons observed to decay to a charm meson and a charmless baryon. The new state is identified as the isospin scalar $\Lambda_c(2940)^+$, due to the absence of an isospin partner in the D^+p mass spectrum. The existance of the $\Lambda_c(2940)^+$ has been confirmed by Belle [24], who observed it in the final state $\Sigma_c(2455)^{++/0}\pi^\mp$. Its spin-parity has yet to be determined.

Besides single charm baryons, double charm baryons are expected to exist with a mass between 3.5 and $3.8\,\mathrm{GeV}/c^2$ for the lightest states [25]. The only evidence for their existance comes from SELEX, which reports an excess of events in $\Lambda_c^+K^-\pi^+$ [26] and $D^+\overline{p}K^+$ [27] at a mass of $3519 \pm 1\,\mathrm{MeV}/c^2$. No evidence of this state is found by FOCUS [28], *BABAR* [29] or Belle [30], even though they have $O(10)$ (FOCUS) and $O(100)$ (*BABAR*, Belle) more reconstructed charm baryons than SELEX.

In the same $\Lambda_c^+K^-\pi^+$ mass spectrum used to search for double charm baryons by Belle, two new regular Ξ_c states are observed with masses of $2978.5 \pm 2.1 \pm 2.0\,\mathrm{MeV}/c^2$ and $3076.7.5 \pm 0.9 \pm 0.5\,\mathrm{MeV}/c^2$ and widths of $43.5 \pm 7.5 \pm 7.0\,\mathrm{MeV}$ and $6.2 \pm 1.2 \pm 0.8\,\mathrm{MeV}$ [30]. The non-zero widths preclude these two states, $\Xi_c(2980)^+$ and $\Xi_c(3077)^+$, from being double-charm baryons. The existence of these two states has since been confirmed by *BABAR* [31]. Belle also observes the isospin partner $\Xi_c(3077)^0$ in the decay $\Xi_c(3077)^0 \to \Lambda_c^+ K_S^0 \pi^-$.

4. CHARMONIUM-LIKE STATES

Many new charmonium or charmonium-like states have been found in recent years. Several of these have received particular attention, since they do not seem to fit in the standard $c\overline{c}$ spectroscopy picture. The most studied of the new states is the $X(3872)$, which was first discovered by Belle [32] in $B^\pm \to K^\pm X(3872), X(3872) \to J/\psi \pi^+\pi^-$ decays. The observation has since been confirmed by several experiments [33–35]. The latest measurements of this decay [36,37] yield a mass $3871.2 \pm 0.6\,\mathrm{MeV}/c^2$ and an upper limit on the width of $\Gamma < 2.3\,\mathrm{MeV}$ at 90% CL.

Several other decay modes of the $X(3872)$ have been observed. Both Belle and *BABAR* have measured the radiative decay $X(3872) \to \gamma J/\psi$ [38,39] with a branching ratio of $(19\pm7)\%$ relative to the $X(3872) \to J/\psi \pi^+\pi^-$ decay mode. The observation of this mode implies that the $X(3872)$ has even charge-conjugation parity. The rate is much lower than what one would expect if the $X(3872)$ was a χ_c' state [40]. Belle also observes the decay $X(3872) \to \overline{D}^0 D^0 \pi^0$ [41]. This decay mode appears to be dominant as it is measured to have a branching fraction 9.7 ± 3.4 times higher than the $X(3872) \to J/\psi \pi^+\pi^-$ decay mode.

The quantum numbers J^{PC} of the $X(3872)$ have been studied using the angular distributions of $X(3872) \to J/\psi \pi^+\pi^-$ decays. Both $B \to X(3872)K$ decays [36] and inclusively produced $X(3872)$ mesons at CDF [42] have been used. The combined analysis exclude all possibilities except 1^{++} and 2^{-+}. The $J = 2$ hypothesis is disfavored by the observation of the near-threshold decay $X(3872) \to \overline{D}^0 D^0 \pi^0$. $J = 1^{++}$ is consistent with the $X(3872)$ being a χ_{c1}' or a $D^0\overline{D}^{*0}$ bound state [43,44]. The latter is currently viewed as the most likely explanation, though tetra-quark models [45] have not been ruled out.

A second interesting charmonium-like state is the $Y(4260)$, discovered by *BABAR* in initial-state radiation (ISR) events, $e^+e^- \to \gamma_{\mathrm{ISR}} Y(4260)$, $Y(4260) \to J/\psi \pi^+\pi^-$ [46]. It is a wide state with a mass of $4259 \pm 8^{+2}_{-6}\,\mathrm{MeV}/c^2$ and a width of $88 \pm 23^{+6}_{-4}\,\mathrm{MeV}$. The observation of $Y(4260)$ in ISR events requires that $J^{PC} = 1^{--}$. The state has been confirmed by CLEO. They performed an energy scan and observe a large increase in the cross section of $e^+e^- \to J/\psi \pi^+\pi^-$ and $e^+e^- \to J/\psi \pi^0\pi^0$ at $\sqrt{s} = 4260\,\mathrm{MeV}$ [47]. The $e^+e^- \to J/\psi \pi^+\pi^-$ cross section is consistent with that measured by *BABAR* in ISR events. The observation of $Y(4260) \to J/\psi \pi^0\pi^0$ implies that it has isospin $I = 0$. *BABAR* has searched for several other possible decay modes of the $Y(4260)$: $p\overline{p}$ [48], $\phi\pi^+\pi^-$ [49] and $D\overline{D}$ [50]. No signals are observed and upper limits on the decay rates are set. The upper limit for the $D\overline{D}$ mode is 7.6 times $\mathcal{B}(Y(4260) \to J/\psi \pi^+\pi^-)$ at 95% CL, which is much smaller than for example $\frac{\psi(3770)\to D\overline{D}}{\psi(3770)\to J/\psi\pi^+\pi^-} \approx 500$ [51]. This suggests that the $Y(4260)$ is not a radially excited ψ state, such as $\psi(4S)$. Currently the most favored explanation is that of a $c\overline{c}g$ hybrid state [52], which is predicted in this mass region.

BABAR also searched for $Y(4260) \to \psi(2S)\pi^+\pi^-$ decays [53]. No signal for the $Y(4260)$ state is found, but a peak is observed at slightly higher mass. The peak is also not consistent with the $\psi(4415)$. A fit with a Breit-Wigner gives a mass of $4354 \pm 16\,\mathrm{MeV}/c^2$ and a width $106 \pm 19\,\mathrm{MeV}$. If $Y(4260)$ is the lowest mass hybrid state, this $Y(4350)$ could be an excitation. However, more studies are needed to confirm the existence of this state and understand its properties.

5. SUMMARY

Charm spectroscopy has seen a lot of activity in the last few years. The $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons appear to be regular 0^+ and 1^+ charm-strange mesons, but new charm mesons and baryons have been found that need further study. In charmonium the $X(3872)$ and $Y(4260)$ have been found to be 1^{++} and 1^{--}, but their decay modes and masses suggest that these are not regular $c\overline{c}$ states. They could be the first examples of a bound $D^0\overline{D}^{*0}$ and a $c\overline{c}g$ hybrid state, respectively. More experimental studies are needed to confirm or refute these hypotheses.

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