Charm and Charm spectroscopy

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Recent developements in D mixing physics and charm spectroscopy will be discussed. Focus will be on the *BABAR* experimental results for the D mixing: first evidence of the D^0-mixing (hadronic D^0 decays), lifetime difference and time-dependent Dalitz plot analysis of $D^0 \to K^+\pi^-\pi^0$. Then, recent results on charm spectroscopy will be presented with particular focus on the new D_s states that have been discovered in the last few years. Some of these states were not expected theoretically: their masses, widths, quantum numbers, and decay modes do not fit the existing spectroscopic classication, which is based mostly on potential model calculations.

1. Introduction

The mixing phenomena has traditionally provided important information on the electroweak interactions. Among the long lived mesons the D mesons system exhibits the smallest effect. The D-mixing is also interesting because it is the only place where the contribution to the CP violation of down-type quarks in the mixing diagram can be explored. Finally understanding the D mixing is an important prerequisite in the search of CP violation in the charm sector. The B-factories have now accumulated sufficient luminosity to observe mixing in this sector. We summarize the result of three different approaches to measure the D mixing parameters at *BABAR*, involving the decays $D^0 \to K^+\pi^-$, $D^0 \to K^+K^-$or $\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^0$.

We present here also a mini-review of a long list of new meson $c\bar{s}$ reported by *BABAR*, BELLE and CLEO. In this short review, we do not present results on $c\bar{u}$ and $c\bar{d}$ resonances and on $c\bar{c}$ states.

All the analyses 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 2008, the *BABAR* experiment recorded a luminosity of 432 fb^{-1}at the $\Upsilon(4S)$ peak , 30.2 fb^{-1} at the $\Upsilon(3S)$, 14.5 fb^{-1} at the $\Upsilon(2S)$ and below and above the peak of the $\Upsilon(4S)$ 53.9 fb^{-1}.

2. D-mixing formalism

Neutral D mesons D^0 and $\bar{D}^0$ are produced as flavor eigenstates. These flavor eigenstates are not equal to the mass and lifetime eigenstates:

$$| D_{1,2}\rangle = p \mid D^0\rangle \pm q \mid \bar{D}^0\rangle \qquad (1)$$

by which they propagate and decay. Therefore, a particle produced as a D^0 may become a $\bar{D}^0$ before its decay. The process is governed by the mass and lifetime differences of the D_1 and D_2 states. These according to

$$| D_{1,2}(t)\rangle = e^{-i(m_{1,2}-i\Gamma_{1,2}/2)t} \mid D_{1,2}\rangle \qquad (2)$$

where $m_{1,2}$, $\Gamma_{1,2}$ are the mass and width of the $D_{1,2}$ states. The mixing parameters are:

$$x = \frac{m_1 - m_2}{\Gamma}$$
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

Mixing will occur if either x or y is nonzero. Estimates within the Standard Model vary form 10^{-4} (only short distance effects) to 1%. The Standard Model contribution to meson mixing is well descibed in the K, B_s and B_d cases by box diagram with W and up-type quarks. In the D meson case one has: $D^0 = (c, \bar{u})$ so that the box contribution for D^0 mixing is given by d-type quarks in the loop (Fig:1). The SM box are tiny because the down-type quarks in the loop make the GIM

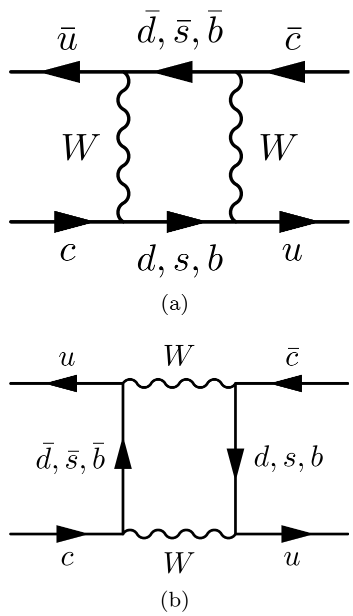

Figure 1. D-mixing Feynman diagram.

suppression extremely effective, the b-quark contribution is CKM suppressed and the s-quark contribution is suppressed by SU(3) breaking.

3. Measurement of D-mixing at *BABAR*

There are several ways to measure the D-mixing :

- Wrong sign semi-leptonic decays (WS) ($D^0 \rightarrow K^+\pi^-$) and right-sign (RS) Cabibbo-Favored (CF) decays ($D^0 \rightarrow K^-\pi^+$)
- Multibody decays ($D^0 \rightarrow K\pi\pi^0$) or ($D^0 \rightarrow K_S\pi\pi$)
- Decays to CP eigenstates ($D^0 \rightarrow K^+K-$ or $D^0 \rightarrow \pi^+\pi^-$)

In this note will be presented only the *BABAR* experimental results: the first evidence of the D^0 mixing (in hadronic D^0 decays), the measurement using the lifetime difference and the time dependent Dalitz plot analysis of the $D^0 \rightarrow K^+\pi^-\pi^0$.

3.1. Hadronic D^0 decays

The analysis is performed looking for the wrong sign decays (WS), e.g. $D^{*+} \rightarrow D^0\pi^+$, with $D^0 \rightarrow K^+\pi^-$. Wrong sign decay may come about either through mixing or through doubly-Cabibbo suppressed (DCS) Feynman diagrams. To distinguish the two cases, we use the decay-time distribution. The decay-time distribution for wrong-sign decays of mesons produced as D^0 may be written as:

$$\Gamma_{WS}(t) = e^{-\Gamma t(R_D + \sqrt{R_D} y^{'} \Gamma t + \frac{x^{'2}+y^{'2}}{4}(\Gamma t)^2)} \quad (3)$$

where $x^{'}$ and $y^{'}$ are related to x and y by

$$\begin{aligned} x^{'} &= x \cos\delta_{K\pi} + y \sin\delta_{K\pi} \\ y^{'} &= -x \sin\delta_{K\pi} + y \cos\delta_{K\pi} \end{aligned}$$

The angle $\delta_{K\pi}$ is the strong relative phase between DCS and CF (Cabibbo favoured) amplitudes. The quantity R_D is the amplitude, in the absence of mixing, for the D^0 to decay by a DCS process. We use 384 fb^{-1} of e^+e^- data, pairing tracks of opposite charge to make D^0 candidates and then pairing these with slow pion tracks to make D^* candidates. We extract the mixing parameters using an unbinned extended maximum likelihood fit, which proceed in three stages. The first step is to fit the $m_{K\pi} - \Delta m$ ($m_{D^{*+}} - m_{K\pi}$) distribution to extract shape parameters in these variables; these are then fixed in the subsequent fits. Next we fit the RS sample to extract the D^0 lifetime and resolution function, using the $m_{K\pi} - \Delta m$ parameters from the previous step to separate the components. Finally we fit the WS sample to determine $x^{'2}$ and $y^{'}$.The results are the following:

$$\begin{aligned} x^{'2} &= (-0.22 \pm 0.30 \pm 0.21) \cdot 10^{-3} \\ y^{'} &= (9.7 \pm 4.4 \pm 3.1) \cdot 10^{-3} \end{aligned}$$

This result is the first **D mixing evidence** [2].

3.2. D^0 mixing life time difference

For D mesons decaying to CP eigenstates, mixing changes the decay time distribution in such a way that we may, to a good approximation, consider the decays exponential with changed lifetimes

$$\tau^+ = \tau^0[1 + |q/p|(y \cos\phi_f - x \sin\phi_f)]^{-1} \quad (4)$$

$$\tau^{-} = \tau^{0}[1+|q/p|(y\cos\phi_f + x\sin\phi_f)]^{-1} \quad (5)$$

Here ϕ_f is the CP-violating phase $\phi_f = arg(\frac{q\bar{A}_f}{pA_f})$, $A_f(\bar{A_f})$ being the amplitude for D^0 ($\bar{D}^0$) decaying to the final state f, τ^0 is the lifetime for decays to final states which are not CP eigenstates, and τ^+ (τ^-) is the lifetime for D^0 $\bar{D}^0$ decays to CP-even states. We can combine the three lifetimes into quantities

$$\begin{aligned} y_{CP} &= \frac{\tau^0}{\langle\tau\rangle} - 1 \\ \Delta Y &= (\tau^0 A_\tau)/\langle\tau\rangle \end{aligned}$$

$\langle\tau\rangle$ is the average of τ^+ and τ^-, and A_τ is their asimmetry $\frac{(\tau^+-\tau^-)}{(\tau^++\tau^-)}$. In absence of mixing both y_{CP} and ΔY are zero. In absence of CP violation in the interference of mixing and decay (ie $\phi_f = 0$), ΔY is zero and $y_{CP} = y$. For this analysis we used 384 fb^{-1} of *BABAR* data, and measure the lifetimes for the CP-even decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, and for $D^0 \to K^-\pi^+$ which is not a CP eigenstates and thus gives τ^0. We fit the decay time distribution of these samples using an unbinned maximum likelihood fit to all five decay modes simultaneously, using separate PDFs for signal decays, mistagged events, mis-reconstructed charm events, and combinatorial background. The results of these decay-time fits are shown in table 1. From the measured lifetime, we extract:

$$y_{CP} = 1.24 \pm 0.39(stat) \pm 0.13(syst)\% \quad (6)$$

$$\Delta Y = [-0.26 \pm 0.36(stat) \pm 0.008(syst)]\% \quad (7)$$

which is evidence for $D^0 - \bar{D}^0$ mixing at the 3-σ level [3], and consistent with CP conservation. This amount of $D^0 - \bar{D}^0$ mixing is consistent with Standard Model predictions.

3.3. Three body decay analysis: $D^0 \to K^+\pi^-\pi^0$

For the D^0 decays to three-body final states, we can modify Equation 3 to give a decay-time distribution for each point in the decay phase space:

$$\begin{aligned} \mathcal{A}(P,t) = \; & e^{-\Gamma t}[|\overline{A_P}|^2 + [|\overline{A_P}A_P|^2 \\ & (y^{''}\cos\delta_P - x^{''}\sin\delta_P)\Gamma t + \\ & |A_P|^2(x^{''2}+y^{''2})(\Gamma t)^2] \end{aligned}$$

Table 1
Measured lifetimes for the different decay modes.

Mode	lifetime fs
$D^0 \to K^-\pi^+$	409.33 ± 0.70
$D^0(D^{*+}) \to K^-K^+$	401.28 ± 2.47
$D^0(D^{*-}) \to K^-K^+$	404.47 ± 2.52
$D^0(D^{*+}) \to \pi^-\pi^+$	407.64 ± 3.68
$D^0(D^{*-}) \to \pi^-\pi^+$	407.26 ± 3.73

In analogy with Equation 3, $\overline{A_P}$ is the amplitude (in the absence of mixing) for D^0 mesons to decay by a DCS process to the point P on the Dalitz plot. The quantity δ_P is the phase of the intermediate states in the decay, relative to some reference resonance. As with the $D^0 \to K^+\pi^-$ case an unknown strong phase $\delta_{K\pi\pi^0}$ between CF and DCS decays prevents us from measuring x and y directly; instead we are sensitive to:

$$\begin{aligned} x'' &= x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0} \\ y'' &= y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0} \end{aligned}$$

The results are the following:

$$\begin{aligned} x^{''} &= (2.39 \pm 0.61 \pm 0.32)\% \\ y^{''} &= (-0.14 \pm 0.6 \pm 0.4)\% \end{aligned}$$

This excludes the no-mixing hypothesis at the 99% confidence level [4].

3.4. Summary

BABAR has found evidence for mixing with different methods: this is an outstanding experimental achievement. The combined world average is inconsistent with no-mixing at 6.7σ. There is no evidence for CPV in the charm mixing yet, but a lot of analyses are still ongoing.

4. Charm spectroscopy: $c\bar{s}$ mesons

4.1. Brief history of $c\bar{s}$ mesons and current situation

Before 2003, only four $c\bar{s}$ meson 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 the $D_{s2}(2573)(2^+)$. The masses predicted by the potential model were in good agreement with the measured masses. All these 4 states are very narrow. After 2003 there were many discoveries of new D_{sJ} states: $D^*_{S0}(2317)^+$[8], $D^*_{S1}(2460)$[9], $D^*_{SJ}(2860^+)$[10], $X(2690)^+$, and $D_{SJ}(2700)^+$[12], [13], that is maybe the same state of $X(2690)^+$.

These states have brought into question potential models. Two masses, $D^*_{sJ}(2317)^+$ and $D_{SJ}(2460)^+$ are very much lower than expected and below the DK and D^*K threshold respectively. With all these new discoveries a comprehensive knowledge of all known D_s mesons is mandatory.

4.2. $D_{S1}(2536)$

Before 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% of confidence level and the quantum numbers were only inferred. We performed a measurement of the mass and of the width using events in the $c\bar{c}$ continuum (232 fb^{-1}). Reconstructing inclusively the decay $D_{S1}(2536) \rightarrow D^{*+}K^0_S$ with $D^{*+} \rightarrow D^0\pi^+$ and D^0 decaying either to $K^-\pi^+$ or to $K^-\pi^+\pi^-\pi^+$, one obtains a mass:

$$m_{D_{S1}} = (2534.85 \pm 0.02 \pm 0.40) MeV/c^2 \quad (8)$$

and a width:

$$\Gamma_{D_{S1}} = (1.03 \pm 0.05 \pm 0.12) MeV \quad (9)$$

This is the first time that a direct measurement of the width is given, rather than just an upper limit [5]. Additionally in another analysis, the $D_{S1}(2536)$ meson was reconstructed exclusively in B decays, with $B \rightarrow D^*D_{S1}(2536)$ (8 modes in total) followed by $D_{S1}(2536) \rightarrow D^*K$. A total of 182 ± 19 events is seen, which gives an observation at the 12σ significance level. 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 [6].

4.3. $D^*_{S0}(2317)^+$ and $D^*_{S1}(2460)^+$

The $D^*_{S0}(2317)^+$ and $D^*_{S1}(2460)^+$ were discovered 5 years ago in $e^+e^- \rightarrow c\bar{c}$ events and they were subsequently observed in B decays. Masses and tight upper limits on width have been set [8],[9]:

$$\begin{aligned} m_{D^*_{S0}} &= (2319.6 \pm 0.2 \pm 1.4) MeV/c^2 \\ \Gamma_{D^*_{S0}} &< 3.8 MeV @ 95\% CL \end{aligned}$$

$$\begin{aligned} m_{D^+_{S1}} &= (2460.2 \pm 0.2 \pm 0.8) MeV/c^2 \\ \Gamma_{D^+_{S1}} &< 3.5 MeV @ 95\% CL \end{aligned}$$

The decay modes and branching fractions are also well measured. Despite a good knowledge of these states, their theoretical interpretation is still unclear: one obvious posssibility is to identify these two resonances with the 0^+ and 1^+ $c\bar{s}$ states, but their masses are well below what is predicted by the potential model. Other interpretations have been proposed: four quark states, DK molecules or $D\pi$ atoms[7].

4.4. $D^*_{SJ}(2860)$

The $D^*_{SJ}(2860)$ resonance was discovered by BABAR in 2006, looking in the $c\bar{c}$ continuum: $e^+e^- \rightarrow D^0K^+X$ and $e^+e^- \rightarrow D^+K^0_SX$, where the $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0$ and $D^+ \rightarrow K^-\pi^+\pi^+$ and where X could be anything. BABAR observed a clear peak 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 [10].

4.5. $D_{SJ}(2700)$

In the same analysis of $D^*_{SJ}(2860)$, BABAR reported a broad enhancement, named X(2690), at the 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 [11] at a similar mass, with a J^P quantum number equal to 1^-, looking at $B^+ \rightarrow \bar{D}^0D^0K^+$ events. 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, looking at events where B decays to $\bar{D}^{(*)}D^{(*)}K$. A clear resonant enhancement is seen around a mass of $2700 MeV/c^2$ in DK and D^*K invariant mass distribution, [12],[13].

4.6. Summary

BaBar has given an impressive list of new results in hadron spectroscopy since 1999. In the $c\bar{s}$ sector, the $D_0^*(2317)$ and $D_{S1}(2460)$ mesons are now very well known experimentally, but no definite interpretation is given theoretically. The $D_{SJ}^*(2860)$ and $D_{SJ}(2700)$ mesons were discovered recently and need more experimental inputs.

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