# Charm and Charm spectroscopy

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Recent developements in D mixing physics and charm spectroscopy will be discussed. Focus will be given to 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 :

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

by which they propagate and decay. Therefore, a particle produced as a $D^0$ 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 propagating according to

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

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 non zero. Estimates within the Standard Model vary form $10^{-4}$ (couting 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 diagram are tiny because the down-type quarks in the loop

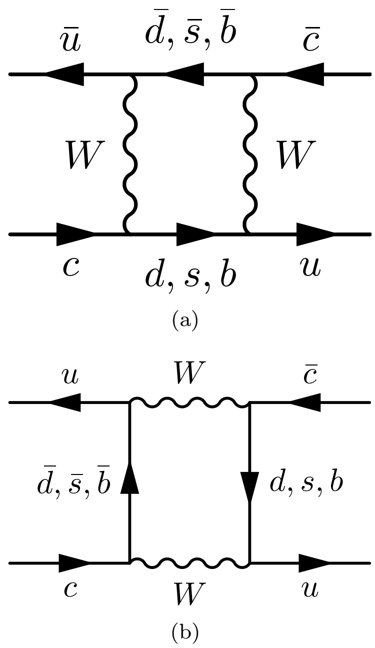


Figure 1. D-mixing Feynman diagram.

makes the GIM 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 perfomed 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) Feymann 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:

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

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

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

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 maximuum likelihhod 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:

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

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 $\phi_f$ 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, $\tau^0$ is the lifetime for decays to final states which are not CP eigenstates, and $\tau^+$ ($\tau^-$) is the lifetime for $D^0$ $\bar{D}^0$ decays to CP-even states. We can combine the three lifetime into quantities

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

$\langle\tau\rangle$ is the average of $\tau^+$ and $\tau^-$, and $A_\tau$ is their asimmetry $\frac{(\tau^+-\tau^-)}{(\tau^++\tau^-)}$. In absence of mixing both $y_{CP}$ and $\Delta Y$ are zero. In absence of CP violation in the interference of mixing and decay (ie $\phi_f = 0$), $\Delta Y$ 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 give $\tau^0$. We fit the decay time distribution of these samples using an unbinned maximuum 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-$\sigma$ level [3], and consistent with CP conservation. This amount of $D^0 - \bar{D}^0$ mixing is consistent with Standard Model predictions.

Table 1
Measured lifetimes for the different decay modes.

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

### 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 the Equation 3 to give a decay-time distribution for each point in the decay phase space:

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

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 $\delta_P$ 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 measuring $x$ and $y$ directly; instead we are sensitive to:

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

The results are the following:

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

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 outastanding experimental achievement. The combined world average is inconsistent with no-mixing at $6.7\sigma$. There is no evidence for CPV in the charm mixing yet, but a lot of analysis 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 mass position, $D_{sJ}^*(2317)^+$ 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 the 2006 the properties of the $D_{S1}(2536)$ meson were not perfectly know: 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 $D_{S1}(2536) \rightarrow D^{*+}K_S^0$ with $D^{*+} \rightarrow D^0\pi^+$ and $D^0$ decaying either to $K^-\pi^+$ or to $K^-\pi^+\pi^-\pi^+$, one obtain a mass:

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

and a width:

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

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 $182 \pm 19$ events is seen, which gives an observation at the $12\sigma$ 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: subsequently observed in B decays. Masses and tight upper limits on width have been set [8],[9]:

$$m_{D_{S0}^*} = (2319.6 \pm 0.2 \pm 1.4) MeV/c^2$$
$$\Gamma_{D_{S0}^*} < 3.8 MeV @ 95\% CL$$

$$m_{D_{S1}^+} = (2460.2 \pm 0.2 \pm 0.8) MeV/c^2$$
$$\Gamma_{D_{S1}^+} < 3.5 MeV @ 95\% CL$$

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 within 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 $e^+e^- \rightarrow D^+K_S^0X$, 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 $8\sigma$ [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 $B^+ \rightarrow \bar{D}^0 D^0 K^+$ 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. No precise measurement was given by this preliminary analysis that it is still in progress [12],[13].

### 4.6. Summary

*BABAR* gave an impressive list of new results 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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