Charm and Charm spectroscopy

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Outline

✓ The BaBar detector and Data sample
✓ D mixing
  ✓ Why is it so important?
  ✓ How to measure the D-mixing
  ✓ Hadronic $D^0$ decays
  ✓ Semi-leptonic decays
  ✓ Lifetime differences
  ✓ Analysis of 3-body decays
✓ Charm meson spectroscopy
  ✓ Overview of the current situation
  ✓ $D_{sJ}$ states
✓ Summary

Not mentioned in this talk: charm baryon spectroscopy
The BaBar Detector

BaBar is also a c factory: 1.3 million Charm events per fb⁻¹

Data collected:

Y(4S): 432 fb⁻¹
Y(3S): 30.2 fb⁻¹
Y(2S): 14.5 fb⁻¹

OffPeak (10.54GeV) + Scan above Y(4S): 53.9 fb⁻¹

The largest world samples on Y(3S) and Y(2S)

Data-taking ended in april 2008

Instrument Flux Return
Solenoid (1.5T)

Silicon Vertex Tracker
Drift Chamber
Electromagnetic Calorimeter

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$D^0$-mixing
Why the D mixing is it so interesting?

✓ It completes the quark mixing picture already seen in the $K, B_d, B_s$ systems

✓ The charm sector is the only place where the contribution to the CP violation of down-type quarks in the mixing diagram can be explored.
  ✓ Flavor physics provides strong constraints on models.
  ✓ Many models poorly tested in $Q=+2/3$ quark sector

✓ Depending on the measured values of the parameters it could indicate new physics

✓ It is an important prerequisite in the search of CP violation in the charm sector
Neutral $D$ mesons ($D^0$ and $\bar{D}^0$) are produced as flavor eigenstates, but they can mix through weak interaction:

$$|D^0\rangle \xrightarrow{\text{weak}} |\bar{D}^0\rangle$$

Time evolution is given by the Schrödinger equation:

$$-i \frac{\partial}{\partial t} \left( |D^0(t)\rangle \right) = \left( M - i \frac{\Gamma}{2} \right)_{\text{weak}} \times \left( |D^0(t)\rangle \right)$$

The mass eigenstates are related to the flavour eigenstates:

$$|q^2\rangle + |p^2\rangle = 1$$

and they propagate according to

$$|D_{1,2}(t)\rangle = e^{-i \left( m_{1,2} - i \frac{\Gamma_{1,2}}{2} \right) t} |D_{1,2}(t=0)\rangle$$

The mixing parameters are

$$x = \frac{(m_1 - m_2)}{\Gamma} \quad (3) \quad y = \frac{(\Gamma_1 - \Gamma_2)}{2\Gamma} \quad (4) \quad \Gamma = \frac{(\Gamma_1 + \Gamma_2)}{2\Gamma} \quad (5)$$

Mixing will occur if either $x$ or $y$ is non zero.
The SM contribution to meson mixing is well described in the $K, B_s$ and $B_d$ cases by box diagram with $W$ and up-type quarks:

In the $D$ meson 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 with down-type quarks in the loop GIM suppression is extremely effective. The $b$-quark contribution is CKM suppressed and the $s$-quark contribution is suppressed by SU(3) breaking.

**Good news:** SM box is tiny: a lot of room for new Physics to show up

**Bad news:** There are long distance contributions due to the fact $m_c \sim$ hadronic scale $K\pi$ intermediate states likely dominate.
How to measure D-mixing

There are several ways to measure D-mixing:

- First evidence of the D\(_0\)-mixing (hadronic D\(_0\) decays)
- Semi-leptonic D\(_0\) decays
- Lifetime difference
- Time-dependent Dalitz plot analysis of D\(_0\)→K\(^+\)π⁻π\(^0\)

I will focus on the BaBar experimental results:

- Wrong sign semi-leptonic decays (WS) (D\(_0\)→K\(^+\)π\(^-\)) and right-sign (RS) Cabibbo-Favored (CF) decays (D\(_0\)→K\(^-\)π\(^+\))
- Multibody decays (Kππ\(^0\)) or (K\(_S\)ππ)
- Decays to CP eigenstates (K\(^+\)K\(^-\) or π\(^+\)π\(^-\))
**Hadronic $D^0$ decays**

Look for wrong sign decays, e.g. $D^{*-}\rightarrow D^0\pi^+$, $D^0\rightarrow K^+\pi^-$:

Two contributions to wrong sign decays:

- Doubly-Cabibbo-Suppressed (DCS) Decay
- Mixing then Cabibbo-favored (CF) decays

Discriminate DCS and mixing using temporal distribution

\[ \Gamma_{WS}(t) = e^{-\Gamma t} \left( R_D \sqrt{\Gamma} \, t + \frac{\Gamma t^2}{4} \right) \]

Assuming $|x| < 1$, $|y| < 1$ and no CPV

\[ x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}, \quad y' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi} \]

$\delta_{K\pi}$ is the strong relative phase between DCS and CF amplitudes
Hadronic $D^0$ decays: results

Fitting procedure:

- Fit $m(K\pi)$, $\Delta m(D^{*+}-m_{K\pi})$ distribution to separate signal and backgrounds
- Fit to RS proper time distribution to determine proper time signal resolution function
- Fit to WS proper time distribution to determine $x'$ and $y'$

First evidence of $D$ mixing

384 fb$^{-1}$

$X'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

$Y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

Correlation $x' , y' = -0.94$

Significance from $\Delta \log L$

The WS branching fractions from independent $\{m_{K\pi}, \Delta m\}$ fits to slices in measured proper time (points)

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**$D^0$ mixing life time difference**

- Study $D^0$ mixing by means of life time difference among $D^0 \rightarrow K^+ K^-$, $\pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$

\[
y_{CP} = \frac{\tau(D^0 \rightarrow K^- \pi^+)}{\tau(D^0 \rightarrow h^- h^+)} - 1
\]

- Mixture of CP odd and CP even states

- CP even states

\[
y_{CP} = y \cos \phi - \frac{1}{2} A_M \times \sin \phi \quad A_M = \left| \frac{q}{p} \right|^2 - 1 \quad \phi \text{ is a weak phase}
\]

- If CP conserved, $A_M = \phi = 0$, $y_{CP} = y$

Also search for CPV by measuring:

\[
A_1 = \frac{\tau(D^0 \rightarrow K^- K^+)}{\tau(D^0 \rightarrow K^- K^+)} - \frac{\tau(D^0 \rightarrow K^+ K^-)}{\tau(D^0 \rightarrow K^- K^+)}
\]

\[
\Delta Y = - \frac{\tau(D^0 \rightarrow \overline{D}^0 \rightarrow K^- \pi^+)}{(\tau(D^0 \rightarrow K^+ K^-) + \tau(\overline{D}^0 \rightarrow K^+ K^-))/2} A_1
\]

*BaBar: hep-ex/0712.2249*
Lifetime ratio measurement

$\tau_{K\pi} = 409.3 \pm 0.7$ fs

$\tau_{K^+K^-} = 401.3 \pm 2.5$ fs

$\tau_{\pi^+\pi^-} = 407.6 \pm 3.7$ fs

$\tau_{\pi^+\pi^-} = 407.3 \pm 3.8$ fs

$\tau = 407.3 \pm 3.8$ fs

3 $\sigma$ evidence for $D^0$-$\bar{D}^0$ mixing
Three body decay analysis: $D^0 \rightarrow K^+\pi^-\pi^0$

Approach similar to $K\pi$, except the time dependence is a function of position in the Dalitz plot:

$$\Gamma_f(m_{12}, m_{13}, t) = e^{-t} \left\{ |A_f|^2 + |\bar{A}_f| |y''\cos\delta_{\bar{f}} - x''\sin\delta_{\bar{f}}| (\Gamma t) + \frac{x''^2 + y''^2}{A} |\bar{A}_f|^2 (\Gamma t)^2 \right\}$$

$x, y$ are rotated of a strong phase for final state

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

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

$$\chi^2 = \frac{1}{2}(2.39 \pm 0.61 \pm 0.32\%)$$

$$\gamma'' = (-0.14 \pm 0.6 \pm 0.4\%)$$

$$R_{\text{mix}} = (x''^2 + y''^2)/2 = (2.9 \pm 0.6) \times 10^{-4}$$

No mixing is excluded at 99% confidence level

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D-mixing summary

☑ Evidence for charm mixing represents an outstanding experimental achievement
☑ Combined world average is inconsistent with no mixing at $6.7\,\sigma$
☑ No evidence for CPV in charm mixing yet
☑ Lot of analysis still on-going
Charm spectroscopy: $c\bar{s}$ mesons
Brief history of $c\bar{s}$ spectroscopy before 2003

A $D_{sJ}$ charmed-strange meson is composed of a $c$ and a $\bar{s}$ quarks.

- All 4 discovered states are very narrow
- $D_s$ through weak decay
- $D_s^* \rightarrow D_s \gamma$ & $D_s \pi^0$
- $D_{s1}(2536)$
- $D_{sJ}(2573)$

$D_s^* , D_{s1}(2536)^+ , D_{sJ}(2573)^+$ well known, but $J^P$ only inferred not measured
The discovery of the new $D_{sJ}$ states has brought into question potential models.

2 Mass positions of $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ very much lower than expected and below the DK and $D^*K$ thresholds respectively.

- $D_{s0}^*(2317)^+$, Apr. 2003: unexpected observation of a narrow resonance in BaBar
- $D_{s1}(2460)$, May. 2003: CLEO BaBar observed a new narrow resonance
- $D_{sJ}^*(2860)^+$, Jul. 2006: new state discovered by BaBar
- $X(2690)^+$, Jul. 2006: broad enhancement seen in BaBar
- $D_{sJ}^*(2700)^+$, Jul. 2006: new state discovered by Belle ($\equiv X(2690)$?)
**D_{s1}(2536)**

Precision measurement of $D_{s1}^- \to D^{*-}K^0$ in continuum $D^*+ \to D^0\pi^+$ $D^0 \to K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$

$M(D_{s1}^+) = (2534.85 \pm 0.02 \pm 0.40)\text{MeV}/c^2$

$\Gamma(D_{s1}^+) = (1.03 \pm 0.05 \pm 0.12)\text{MeV}$

First measurement of the width

$B \to D(*)D_{s1}^+$ (8 modes) $D_{s1}^+ \to D^{*0}K$

First observation of $D_{s1}$ in $B$ decays

$N = 182 \pm 19$ events $12\sigma$

$M(D_{s1}^+) = (2534.78 \pm 0.31 \pm 0.40)\text{MeV}/c^2$

$J=1$ is favored


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**D_{s0}^*(2317)^+ and D_{s1}^+(2460)**

- Discovered 4 years ago in $e^+e^-\to c\bar{c}$ events: subsequently observed in B decays
- Comprehensive study of decays to $D_s^+$, plus one or two $\pi^+/-,\pi^0$ or $\gamma$
- Masses and tight upper limit on widths

\[
\begin{align*}
M(D_{s0}^*) &= (2319.6 \pm 0.2 \pm 1.4)\text{MeV}/c^2 \\
\Gamma(D_{s0}^*) &< 3.8\text{MeV} @ 95\% \text{ CL} \\
M(D_{s1}^+) &= (2460.2 \pm 0.2 \pm 0.8)\text{MeV}/c^2 \\
\Gamma(D_{s1}^*) &< 3.5\text{MeV} @ 95\% \text{ CL}
\end{align*}
\]

- A search for neutral and doubly charged partners of $D_{s0}^*(2317)^+$ mesons has been done (tetra quark model). No evidence of such states near 2317 MeV.
- $J^P: 0^+$ for $D_{s0}^*(2317)$ and $1^+$ for $D_{s1}(2460)$
- Interpretation of these new states still unclear because the masses of these 2 states are very unusual:
  - Identify them as the $0^+$ and $1^+$ $c\bar{s}$ states (strong difficulties with potential model)
  - 4 quark states? DK molecule? $D\pi$ atom? Chiral symmetry?

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**$D_{sJ}^*(2860)$ and $X(2690)$?**

Looking to very small cross section in the $c\bar{c}$ continuum:

$e^+e^-\rightarrow D^0(K^-\pi^+, K^-\pi^+\pi^0)K^+X$ and $e^+e^-\rightarrow D^+(K^-\pi^+\pi^+)K_0^S X$

BaBar discovered a new structure at 2.86 GeV/$c^2$

There was also a bump at 2690 MeV/$c^2$ is another resonance? Probably $X(2690)$

- $M(D_{sJ}^*) = (2856.6 \pm 1.5 \pm 5.4)$ MeV/$c^2$
- $\Gamma(D_{sJ}^*) = (47 \pm 7 \pm 10)$ MeV

- $M(X?) = (2688 \pm 4 \pm 3)$ MeV/$c^2$
- $\Gamma(X?) = (112 \pm 7 \pm 36)$ MeV

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Belle discovered new resonance in $B^+ \rightarrow D^0 D_{sJ}, D_{sJ}^+ \rightarrow (D^0 K^+)$

$M(D_{sJ}) = (2708 \pm 9^{+11}_{-10})$ MeV/$c^2$

$\Gamma(D_{sJ}) = (108 \pm 23^{+36}_{-31})$ MeV

$J^P = 1^-$ favored

Same resonance as seen by BaBar in continuum, $X(2690)$?
Mass and width are consistent, same decay mode

Study of $B \rightarrow D(*) D(*) K$ decays in BaBar (22 modes)
Enhancement observed around 2690 MeV/$c^2$ in $D K$ and $D^* K$
Dalitz plot analysis in progress

No signal of $D_{sJ}^*(2860)$ in $B$ decays

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Charm mesons spectroscopy summary

✓ Several new charmed states discovered in the last few years.
✓ Many new states are waiting for a classification in the quark model (potential models are in trouble)
✓ More information is needed
✓ Spectroscopy will provide more surprises!
Back-up slides
Event selection in the D-mixing analysis

There are two keys sperimental features used in D⁰-mixing analysis:

- The flavor tag by D∗
- p(D∗)>~2.5 GeV to eliminate D⁰ from B decays

Beam-constrained vertex fits of K, π, π_{tag} tracks as shown in figure.

π_{tag} charge gives D flavor at production.
Semileptonic $D^0$ decays: $D^0 \rightarrow K^* \ell \nu$

In the limit of small mixing and no CP violation mixed $D^0$ states decaying semi-leptonically have a simpler time dependence:

- WS time-dependence for semi-leptonic analyses is well-distinguished from exponential
- No DCS decays in the semi-leptonic $D^0$ decays
- Missing neutrino makes $D^0$ reconstruction harder
- semileptonic decays gives direct access to mixing rate $R_M$

\[
R_M = \frac{\int_0^\infty dt \mathcal{P}(D^0 \rightarrow \overline{D}^0 \rightarrow X^+ \ell^- \overline{\nu}_\ell) \propto R_M t^2 e^{-\Gamma t}}{\int_0^\infty dt \mathcal{P}(D^0 \rightarrow \overline{D}^0 \rightarrow X^- \ell^+ \nu_\ell) \approx \frac{x^2 + y^2}{2}}
\]

No evidence for mixing

$344 \text{fb}^{-1}$  $R_M = (-13,12) \times 10^{-4} \ @ \ 90\% \ C.L.$