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$D^0\overline{D^0}$ mixing and other recent charm results from BABAR*

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Abstract Studies in which BABAR data have shown evidence for mixing in the neutral charm meson system are presented. A new measurement of the lifetime difference parameter $y_{\rm CP} = (1.16\pm0.22\pm0.18)\%$ is described. Results are also presented from a systematic study of DK and D^*K invariant mass distributions from a 470 fb^-1 sample of asymmetric e^+e^- interactions recorded by the BABAR detector at the PEP-Ⅱ storage rings. A new charmed-strange meson has been observed with mass $[3044\pm8_{\rm stat}(^{+30}_{-5})_{\rm syst}]\ {\rm MeV}/c^2$ and width $[239\pm35_{\rm stat}(^{+46}_{-42})_{\rm syst}]\ {\rm MeV}/c^2$.

Key words keyword, mixing, oscillations, charm, meson, spectroscopy

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1 Introduction

In this paper, we describe recent results from the BABAR collaboration relating to production and decay of charm mesons. Evidence for $D^0\overline{D^0}$ oscillations in four independent measurements that are described in Sections 3 and 4. Results of a study of D_s meson resonance production in D^*K systems using the full BABAR data sample are then presented in Section 5.

A brief summary of these results, their relation to those available from other experiments and an assessment for the future prospects are made in Section 6.

We begin, in Section 2, with a short introduction to $D^0\overline{D^0}$ oscillations.

2 Oscillations in the $D^0\overline{D^0}$ system

Particle-antiparticle oscillations can occur in any neutral meson system. They arise from beating of the two mass eigenstates that propagate differently in time, and mix to produce the meson flavour states. Oscillations depend upon normalized differences

$$x = \frac{m_1 - m_2}{\Gamma}\ ;\ y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}\ ;\ \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}, \qquad (1)$$

in the masses and decay rates, $m_{1,2}$ and $\Gamma_{1,2}$, respectively, of these states and are absent if $x = y = 0$. The phenomenon was first observed in the K^0 system, then in those of the B^0 and B_s mesons. Oscillations in the D^0 system (the only case for mesons consisting of up-type quarks[2)]) were first discussed in 1975 [1], but evidence for them has only been found in the past two years [2–6] with values for x and y of $\sim 1\%$ [7] - very much smaller than those for the other systems.

2.1 Theoretical considerations

Figure 1(a) represents the leading term in the standard model, SM, which contributes mostly to x through $\Delta C = 2$ transitions (C is the charm quantum number).

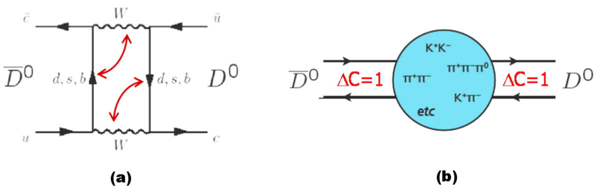

Fig. 1. (a) Short range $\Delta C = 2$ mechanism contributing to mixing in the $D^0\overline{D^0}$ system. The d,s,b quarks and W bosons can be switched. (b) Long range contributions.

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2) The π^0, η and η' are their own antiparticles and the T^0 is expected to decay too fast for mixing to occur.

This predicts very little mixing ($x<10^{-5}$) [8, 9] since the SM was designed to produce large cancellation $\sim(m_\mathrm{s}^2-m_\mathrm{d}^2)/m_\mathrm{c}^2$ of d and s contributions [10], and also because the contribution from b quarks is heavily suppressed by its small Cabibbo-Kobayashi-Moskawa (CKM) coupling to the u quark.

Contributions from new physics (NP) can lead to larger values for x or y [11–14], and can also produce CP violation in mixing. However, it was observed [15] that a sum over real, intermediate states, of second order, long range terms illustrated in Figure 1(b) could contribute significantly (mostly to y). Theoretical uncertainty exists on how to estimate these sums [16–19] and a range of values for x and y from as low as 10^{-7} up to 10^{-2} have been quoted [13, 20, 21]. The present experimental results fit well into the higher range, but the possibility that NP may be involved cannot be ruled out. Theoretical consensus appears to be that

- NP is not ruled out by present measurements.
- Short range SM effects lead to $x,y\ll 1\%$;
- Long range SM effects could lead to x, $y\sim 1\%$, as observed, but $|x|>|y|$ is not expected; and
- CP violation (CPV) in the SM is expected to be negligible at present experimental sensitivities and would signify unambiguous evidence for NP were it observed.

2.2 D⁰ decays

The mass eigenstates, D_1, D_2, are related to the D flavour states by

$$\left.\begin{aligned}|D_1\rangle &= p|D^0\rangle+q|\overline{D^0}\rangle\\ |D_2\rangle &= p|D^0\rangle-q|\overline{D^0}\rangle\end{aligned}\right\}\ \begin{aligned}|p|^2+|q|^2 &= 1\\ \arg\{q/p\} &= \phi_\mathrm{M}.\end{aligned}\qquad(2)$$

Because of mixing, $\mathrm{D^0}$ decay rates do not follow an exponential form. They are governed by the time-dependences $\mathrm{e}^{\mathrm{i}(m_{1,2}+\mathrm{i}\Gamma_{1,2})t}$ of the mass eigenstates $\mathrm{D}_{1,2}$ and by the parameter

$$\lambda_\mathrm{f}=\left(\mathrm{q}\bar{\mathcal{A}}_\mathrm{f}\right)/\left(\mathrm{p}\mathcal{A}_\mathrm{f}\right)\qquad(3)$$

$$\arg\{\lambda_\mathrm{f}\}=\theta_\mathrm{f}=\phi_\mathrm{M}+\phi_\mathrm{f}+\delta_\mathrm{f}.\qquad(4)$$

The decay amplitudes $\mathcal{A}_\mathrm{f}=\langle f|H|D^0\rangle$ and $\bar{\mathcal{A}}_\mathrm{f}=\langle f|H|\overline{D^0}\rangle$ describe, respectively, the processes $\mathrm{D^0\to f}$ and $\mathrm{D^0\to f}$) and have relative weak and strong phases ϕ_f and δ_f.

If CP is conserved in mixing, $p=q=1/\sqrt{2}$ and $\phi_\mathrm{M}=0$. If it is conserved in decay, then $\phi_\mathrm{f}=0$. If f is a CP-eigenstate, then $\phi_\mathrm{f}=\delta_\mathrm{f}=0$ and $\lambda_\mathrm{f}=\pm\mathrm{e}^{\mathrm{i}\phi_\mathrm{M}}$.

In decays of $\mathrm{D^0}$ to final states f accessible to either $\mathrm{D^0}$ or $\overline{\mathrm{D^0}}$ (e.g. $\mathrm{K^+K^-}$, $\mathrm{K^-\pi^+}$, etc), mixing and direct decay interfere, as illustrated in Fig. 2.

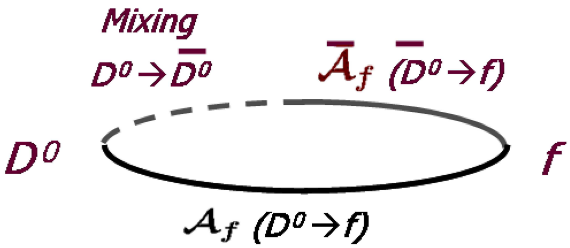

Fig. 2. Decay to final state f accessible to $\mathrm{D^0}$ and $\overline{\mathrm{D^0}}$.

The dependence upon decay time t of the number of $\mathrm{D^0}$ś N is given, to second order in x and y ($\ll 1$), by

$$N(t)=N(0)\mathrm{e}^{-\Gamma t}\times[1+|\lambda_\mathrm{f}|(y\cos\theta_\mathrm{f}-x\sin\theta_\mathrm{f})(\Gamma t)+\frac{x^2+y^2}{4}|\lambda_\mathrm{f}|^2(\Gamma t)^2].\qquad(5)$$

The first term corresponds to direct decay and the term, quadratic in t, to mixing. The middle term, linear in t, is due to the interference between these. In most BABAR analyses, CPV is ignored and then $\theta_\mathrm{f}=\delta_\mathrm{f}$.

3 Evidence for mixing in “wrong sign” decays

The BABAR collaboration reported the first evidence for $\mathrm{D^0}$ oscillations [2] in a large sample of “wrong sign” (WS) decays $\mathrm{D^0\to K^+\pi^-}$1). More recently, they also reported evidence in decays to $\mathrm{K^+\pi^-\pi^0}$ [22]. WS decays are either doubly Cabbibo-suppressed (DCS) or, as in Fig. 2 must proceed through mixing followed by Cabibbo-favoured (CF) decay.

Careful comparison of the decay time distributions in Eq. (5) for WS and “right-sign” (RS) decays was used to extract values for the mixing parameters. In RS decays, λ_f (ratio of DCS to CF decay amplitudes) was small, $\sim 6\times10^{-2}$, so these decays were almost purely exponential. In WS decays, λ_f was large so deviations from exponential decay were large enough to be observable in the BABAR samples used.

Identification of RS and WS decays required efficient tagging of the D flavours ($\mathrm{D^0}$ or $\overline{\mathrm{D^0}}$) at production. Each candidate was required to come from a $\mathrm{D^{*+}\to D^0\pi_s^+}$ decay, where π_s was a low momentum pion. $\mathrm{D^*}$'s were identified by the value of $\Delta\mathrm{M}$, the difference between the invariant mass M of the $\mathrm{D^0}$

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1)Unless explicitly stated otherwise, charge conjugate states are implied.

daughters and that of the $D^0\pi_s^+$ system. The $D^0/\overline{D^0}$ flavour was determined by the sign of the slow pion π_s charge.

In these, as in all BABAR mixing analyses, selection of center of mass momentum of the D^0 above 2.7 GeV/c was effective in excluding D^0's from B decays that would distort the observed decay time distribution.

3.1 WS $K^+\pi^-$ Decays

Samples of approximately 4,000 WS and 1.1 M RS $K\pi$ decays were selected. The RS events were used to determine the decay time resolution parameters which were common to RS and WS samples. Resolution was comparable to the D^0 lifetime, so a good model for it was essential.

A simultaneous fit was made to the form in Eq. (5) for the WS sample and an exponential form for the RS events, each convoluted with the time resolution. Backgrounds under the WS sample were carefully studied and were also modelled in the fit. A significant difference between WS and RS distributions due to mixing was observed.

The effect of mixing was most easily seen in Fig. 3(a), where the ratio of WS/RS events as a function of decay time t was plotted. With no mixing, the distribution would be flat, as indicated by the horizontal line in the figure at the level, $\sim 3.5\times10^{-3}$, of the DCS/CF rate. Significant deviations from this line were evident, however with the anticipated linear variation expected from the interference term in Eq. (5)[1]. This constituted strong evidence for mixing.

The strong phase $\theta_f = \delta_f$ in Eq. (5) was unknown, so the fit determined only rotated mixing parameters x'^2 and y' where:

$$\left.\begin{aligned} x' &= x\cos\delta_f + y\sin\delta_f \\ y' &= y\cos\delta_f - x\sin\delta_f \end{aligned}\right\}, \qquad (6)$$

and not x or y.

Likelihood contours for the fit are shown in the x'^2, y' plane in Fig. 3(b). Errors have been expanded to accomodate systematic uncertainties. These arose primarily from parametrization of the time resolution and of the distribution of background events in the WS system. The central values for x'^2 and y' are almost 4 contours (3.9 σ) from the values (0,0) expected for no mixing.

As a check on the assumption of CP conservation, fits were also made to D^0 and $\overline{D^0}$ samples separately. They agreed well within uncertainties, showing no evidence for CPV.

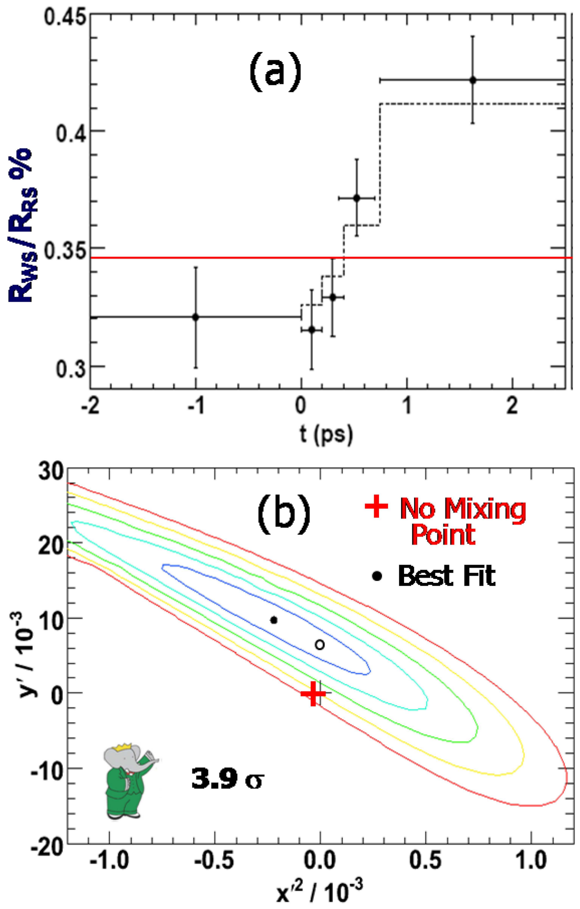

Fig. 3. (a) Ratio of $D^0\to K^+\pi^-$ and $D^0\to K^-\pi^+$ event yields as a function of decay time t. (b) Likelihood contours in the x'^2, y' plane from the fit to the WS decay time distribution described in the text. The contours have been stretched to account for the systematic uncertainties. The best fit parameters are indicated by a solid dot. The "no mixing" point is indicated by a diagonal cross.

3.2 Mixing in $D^0\to K^+\pi^-\pi^0$ Decays

The BABAR collaboration [22] has also reported evidence for mixing from a time-dependent Dalitz plot analysis of WS decays to the three-body system having an additional π^0 meson. This system is similar to the two-body one, except that the final state f is now any point in the $K^+\pi^-\pi^0$ phase space, specified by its Dalitz plot coordinates s_0 and s_+, the squares of invariant masses of $K^+\pi^-$ and $K^+\pi^0$ systems, respectively.

For these WS decays, the expected time-dependence is also given by Eq. (5). However, the parame-

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[1] The quatratic term was strongly suppressed by the factor x^2+y^2.

ter $\lambda_{\rm f}$ now depends on the coordinates ($s_0,\ s_+$) of f. With CP conservation, it is the ratio of decay amplitudes $\bar{\mathcal{A}}(s_0,\ s_+)$ for CF decay ($\overline{\rm D^0}\rightarrow {\rm K}^+\pi^-\pi^0$) and $\mathcal{A}(s_0,\ s_+)$ for direct DCS decay at that point.

In the BABAR analysis, CP was assumed to be conserved and separate models were defined for CF and DCS amplitudes, in each case a linear combination of Breit-Wigner (BW) amplitudes describing their different Kπ and ππ resonance structures. Two independent sets of parameters were introduced to define these models.

The strong phase $\delta_{\rm f}$ in this decay mode could be written as

$$\delta(s_0,s_+)=\delta_{{\rm K}\pi\pi}+\arg\left\{\frac{\bar{\mathcal{A}}(s_0,\ s_+)}{\mathcal{A}(s_0,\ s_+)}\right\}_{\rm model}, \tag{7}$$

where $\delta_{{\rm K}\pi\pi}$ was a constant, strong phase difference between ${\rm D}^0$ and $\overline{\rm D^0}$ decays that arose from the strong effects in the decay, and the second term came from the two models. $\delta_{{\rm K}\pi\pi}$ was unknown, so that fitting the WS Dalitz plot to the distribution in Eq. (5) could only determine rotated mixing parameters

$$\left.\begin{aligned} x'' &= x\cos\delta_{{\rm K}\pi\pi}+y\sin\delta_{{\rm K}\pi\pi}\\ y'' &= y\cos\delta_{{\rm K}\pi\pi}-x\sin\delta_{{\rm K}\pi\pi}.\end{aligned}\right\}. \tag{8}$$

Approximately 660,000 RS (${\rm K}^-\pi^+\pi^0$) and 3,000 WS (${\rm K}^+\pi^-\pi^0$) flavoured-tagged decays were extracted, from a 384 fb^{-1} sample of ${\rm e}^+{\rm e}^-$ interactions. Dalitz plots for these events are shown in Figs. 4(a) and (b), respectively.

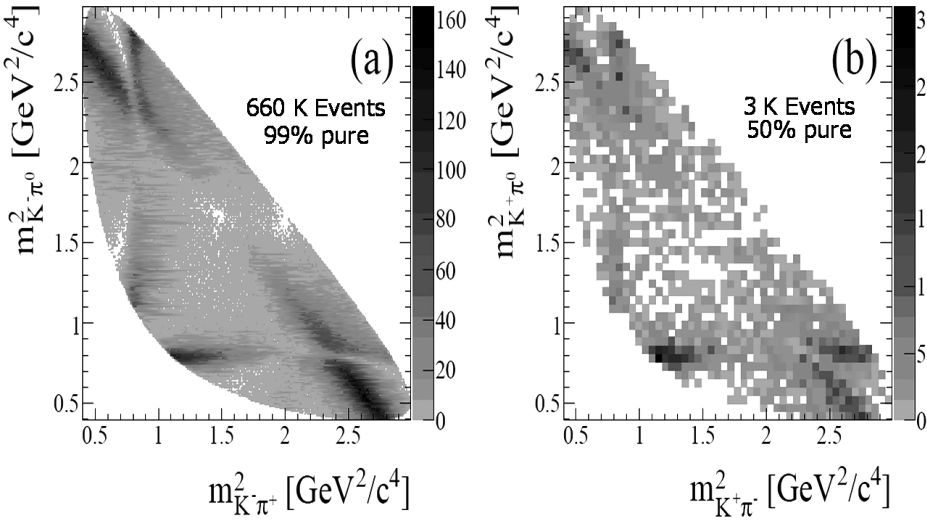

Fig. 4. Dalitz plots (squared invariant masses $s_0=m^2_{K^+\pi^-}$ vs. $s_+=m^2_{K^+\pi^0}$) for (a) RS decays to $\overline{D^0}\rightarrow K^+\pi^-\pi^0$ and (b) WS decays to $D^0\rightarrow K^+\pi^-\pi^0$.

As in the ${\rm K}^+\pi^-$ analysis, the RS events provided crucial parameters for the time resolution. They also provided parameters for the CF decay amplitude model. A fit to the time-integrated RS Dalitz plot was made for this purpose. Strictly, CF decays dominated the RS plot and a very small contribution from events that mixed and then experienced DCS decay were neglected and $\bar{\mathcal{A}}(s_0,\ s_+)$ was taken to be independent of t.

This amplitude was then used in Eq. (5), together with a similar Breit-Wigner model, with different parameters, for the DCS amplitude $\mathcal{A}(s_0,\ s_+)$ to describe the time-dependent WS Dalitz plot. A fit to this model was made to the combined sample of ${\rm D}^0$ and $\overline{\rm D^0}$ decays to determine both the DCS BW model parameters and values for x'' and y'' given in Table 1.

A confidence level test, similar to that used in the WS ${\rm K}^+\pi^-$ case was made. These results were found to indicate evidence for mixing at the 3.1 σ level. The major systematic uncertainties were associated with the assumptions in the BW model and in the description of the large background under the WS events. Estimates of these were included in the computation of the confidence level.

Table 1. Rotated mixing parameters x'' and y'' from fits to BABAR data described in the text. The first error is statistical and the second that attributed to systematic effects.

Sample	x'' (%)	y'' (%)
${\rm D}^0$ and $\overline{\rm D^0}$	$2.61^{+0.57}_{-0.68}\pm0.39$	$-0.06^{+0.55}_{-0.64}\pm0.34$
${\rm D}^0$ only	$2.53^{+0.54}_{-0.63}\pm0.39$	$-0.05^{+0.63}_{-0.67}\pm0.50$
$\overline{\rm D^0}$ only	$3.55^{+0.73}_{-0.83}\pm0.65$	$-0.54^{+0.40}_{-1.16}\pm0.41$

This procedure was also performed separately for D^0 and $\overline{D^0}$ samples to obtain values for x'' and y'' also listed in Table 1, indicating no evidence for CPV.

4 Evidence for mixing in lifetimes for decays to CP eigenstates

The BABAR collaboration has reported further evidence for D^0 oscillations in two independent measurements using D^0 decays to CP-even eigenstates K^+K^- and $\pi^+\pi^-$ [23, 24].

If CP is conserved, such decays have, effectively, the lifetime, τ of the D_1)[1]. The quantity

$$y_{\rm CP} \approx y = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^+h^-)} - 1, \qquad (9)$$

where the Cabibbo-favoured decay to $K^-\pi^+$ (with mixed CP) is compared with that for decay to the CP-even states h^+h^- (h=K or π), then provides an estimate for y based on CP conservation.

An asymmetry $A_\tau = (\tau^- - \tau^+)/(\tau^- + \tau^+)$ in lifetimes τ^+ (for $D^0 \to h^+h^-$) and τ^- (for $\overline{D^0} \to h^+h^-$) would provide information on CPV parameters p, q and their weak phase $\phi_{\rm M}$.

$$A_\tau = \frac{1}{2}\left(\left|\frac{q}{p}\right|^2 - 1\right)\cos\phi_{\rm M} - x\sin\phi_{\rm M}. \qquad (10)$$

BABAR measured $y_{\rm CP}$ and its asymmetry, ΔY, related to A_τ by $\Delta Y = (1 - y_{\rm CP})A_\tau$. With no mixing, $y_{\rm CP} = 0$. With no CPV, $A_\tau = 0$.

Using a 384 $\rm fb^{-1}$ sample of e^+e^- interactions, the BABAR collaboration identified two disjoint samples. One sample, reported in Ref. [23], consisted of flavour-tagged K^-K^+, $\pi^+\pi^-$ and $K^-\pi^+$ decays. The other sample, reported in Ref. [24], contained untagged K^+K^- and $K^-\pi^+$ decays.

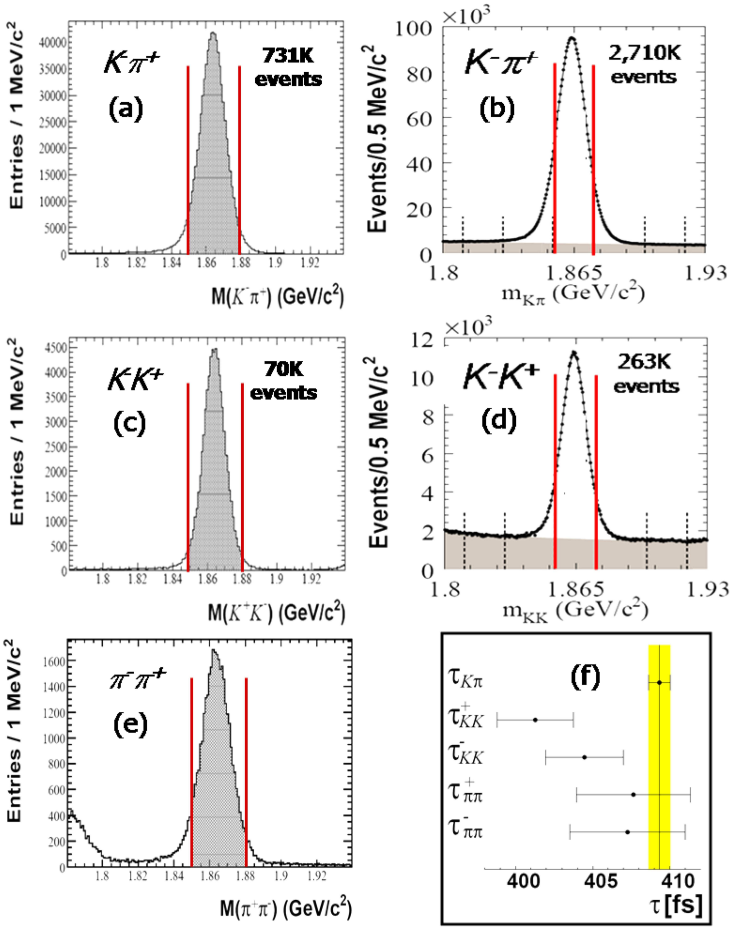

Fig. 5. Invariant mass distributions for D^0 decay daughter pairs from a 384 $\rm fb^{-}1$ e^+e^- sample from the BABAR detector. $K^-\pi^+$ combinations are in (a) and (b), K^-K^+ in (c) and (d) and $\pi^-\pi^+$ in (e). The signal regions used to extract lifetimes are delineated by solid, vertical lines. Events in the tagged sample are in (a), (c) and (e). Lifetimes obtained for these are shown in (f). (b) and (d) are the disjoint, untagged events.

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[1] Our convention is that $CP|D^0\rangle = +|\overline{D^0}\rangle$.

In each case, similar selection criteria were applied to the $K^-\pi^+$ decays as to their CP-even counterparts so that systematic uncertainties in their lifetime ratios would be minimized.

Distributions of the invariant masses of the D daughter pairs are shown in Figs. 5(a)-(e). Backgrounds under the D signals in the tagged sample were very small due largely to the D^* requirement. The untagged sample was considerably larger, but so were its backgrounds.

Events in the signal region in each of the decays were fit to exponential time distributions, convolved with Gaussian resolution functions, to obtain lifetimes for each mode. Results for the tagged sample are in Fig. 5(f) where the difference in lifetimes for $K\pi$ and KK modes is evident.

Lifetimes for the untagged $K^-\pi^+$ and K^-K^+ samples also differ significantly

$$\begin{aligned}\tau_{K^-\pi^+} &= (410.39\pm0.38)\ \text{fs}\\ \tau_{K^-K^+} &= (405.85\pm1.00)\ \text{fs}.\end{aligned}$$

In deriving these results, considerable care was taken to correctly characterize the time dependence of the main backgrounds, and to include this in the lifetime fits.

The values for $y_{\rm CP}$ from each sample are given in Table 2. The results come from completely independent samples and analyses, and they agree well. Each result shows clear evidence for mixing.

The value for $y_{\rm CP}$ resulting from combining the tagged and untagged samples is also given in Table 2. Statistical errors were treated as usual for independent results, but the systematic uncertainties were taken as 100% correlated.

Table 2. Values for $y_{\rm CP}$ obtained from BABAR lifetime ratio measurements. The tagged result is for the combined samples of K^+K^- and $\pi^+\pi^-$ decays. The untagged result comes only from K^+K^-. In each case, the first uncertainty is statistical, the second is systematic. The HFAG result is the world average all measurements.

Analysis	$y_{\rm CP}$	Mixing significance
Tagged [23]	$(1.24\pm0.39\pm0.13)\times10^{-2}$	3.1 σ
Untagged [24]	$(1.12\pm0.26\pm0.22)\times10^{-2}$	3.3 σ
Averaged	$(1.16\pm0.22\pm0.18)\times10^{-2}$	4.1 σ
HFAG	$(1.107\pm0.217)\times10^{-2}$	5.0 σ

These results from BABAR represent evidence for mixing at the 4.1 standard deviation level, and are in excellent agreement with the world average from the Heavy Flavour Averaging Group (HFAG) [7].

The value obtained for the asymmetry was

$$\Delta Y=(-0.26\pm0.36\pm0.08)\times10^{-2}.$$

These results show clear evidence for mixing ($y_{\rm CP}\neq0$) at the 3.1 σ, but no evidence for CPV ($\Delta Y\sim0$).

The main sources of systematic uncertainty for the untagged measurement were uncertainties in the parametrization of the two backgrounds and smaller effects arising from the alignment of the vertex detector. The lifetimes were also affected by the choice of signal window. In both analyses, major systematic effects that could have influenced lifetime measurements were largely cancelled in the evaluation of the lifetime ratios.

5 Spectroscopy of the D_s system

The excited D_s spectrum is not yet fully understood. The $L=1$ mesons in the $c\bar{s}$ system are thought to be made up from hydrogen atom-like states shown in Fig. 6. Doubts on this simple picture persist, however, since the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ states have masses below DK and D^*K thresholds, respectively, in contradiction to calculations [25–28] that have been able to correctly predict masses of other D_s and D systems. Two further states are now believed to exist with higher masses, the $D^*_{s1}(2710)$ [29] and the $D^*_{sJ}(2860)$ [30]. The former has been seen by the Belle collaboration, in the DK system from $B\rightarrow DKK$ decays, and a spin-parity J^P assignment of 1^- has been made. The spin of the $D^*_{sJ}(2860)$ is unknown may be high since it is not seen in B decay.

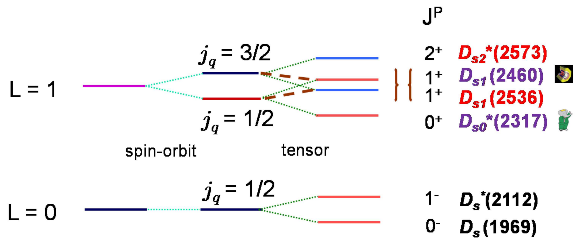

Fig. 6. $L=1$ mesons in the $c\bar{s}$ system.

New scans of the positively charged DK and D^*K systems in the full BABAR data sample from e^+e^- continuum production near the $\Upsilon(4S)$ resonance have been made [31] and results are described here.

Two DK modes $D^0(\rightarrow K^-\pi^+)\ K^+$ and $D^+(\rightarrow K^-\pi^+\pi^+)\ K^S_0$ were included. Five D^*K channels, were selected with D^{*+} decays to $D^0\pi^+$ and $D^+\pi^0$ and $D^{*0}\rightarrow D^0\pi^0$. Each was identified by a peak at about $0.14\ \text{GeV}/c^2$ in the distributions of ΔM, the difference in invariant masses of the $D^0\pi$ and D^0 systems.

D^0 modes were $K^-\pi^+$, $K^-\pi^+\pi^0$ and $K^-\pi^+\pi^+\pi^-$, and D^+ were included only in the $K^-\pi^+\pi^+$ mode.

Two separate $(DK)^+$ and the combined five $(D^*K)^+$ invariant mass distributions are shown, respectively, in Figs. 7(a), (b) and (c).

In the $(DK)^+$ plots, Figs. 7(a) and (b), events in which the D meson could be identified as the decay product of a $D^* \rightarrow D\pi$ decay were removed.

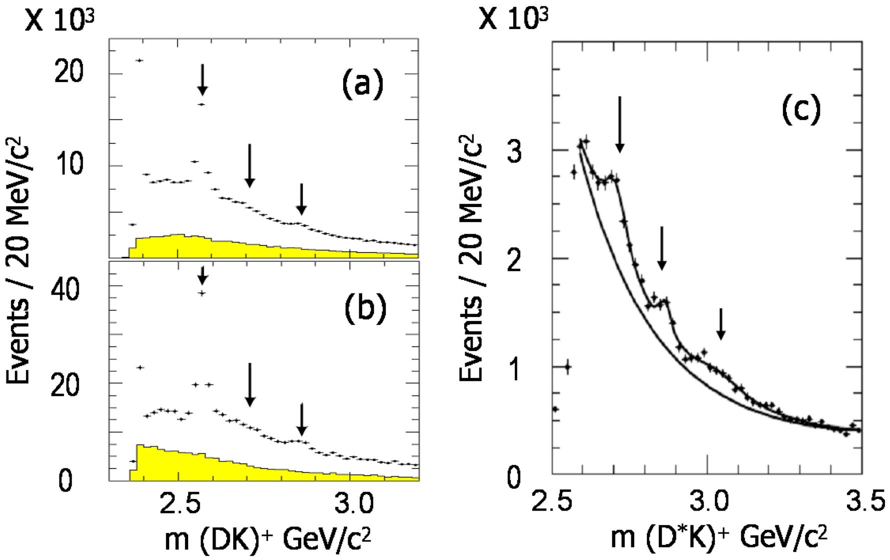

Fig. 7. Invariant mass distributions for (a) D^0K^+ and (b) $D^+K^0_S$ combinations. Shaded distributions are from sidebands in the D^0 daughter invariant mass spectra. In (c) the invariant mass distribution for five charge combinations corresponding to a positively charged D^*K system is shown. D^* sideband distributions have been subtracted. The solid curve is a fit described in the text.

The most prominent feature is the narrow $D^*_{s2}(2573)$, indicated by an arrow. The one bin peak near 2400 MeV/c^2 is due to $D_{s1}(2536) \rightarrow D^*K$ decays in which the D^* batchelor pion is missing. (With $J^P = 1^+$, it is forbidden to decay to DK).

Arrows indicate two other peaks, absent from the D sidebands, in each combination. These are consistent with interpretation as the $D^*_{s1}(2710)$ and $D^*_{sJ}(2860)$, and represent further confirmation of the former state, originally reported by BABAR in this decay mode [30] to be at 2688 MeV/c^2 and seen by Belle at 2710 MeV/c^2 in B decay.

In Fig. 7(c), sideband-subtracted invariant mass distributions for the five D^*K modes are combined. Arrows indicate peaks for the $D^*_{s1}(2710)$ and $D^*_{sJ}(2860)$, the first observation of these states in the D^*K system, ruling out $J^P = 0^+$ assignments for them. Their decays to DK, however, suggest they have natural parity ($1^-, 2^+, \ldots,$ etc.) The helicity angles for these states were also investigated and confirm this assignment in each case.

A fit to the mass spectrum in Fig. 7(c) was made. The background was parametrized with a threshold function that provided a good description of the MC sample, generated without these resonances. This is shown as the solid line in the plot. Masses and widths of $D^*_{s1}(2710)$ and $D^*_{sJ}(2860)$ from this fit agree well with those from the DK spectra.

A further, broad peak above this background is indicated by the third arrow at a mass of about 3.04 GeV/c^2. It has a significance of 6 σ. This is not seen in the DK spectra.

A combined fit to the DK and D^*K spectra was made with this new peak added as an *S*-wave BW resonance in the D^*K system. Masses and widths of the $D^*_{s1}(2710)$ and $D^*_{sJ}(2860)$ were constrained to be

Table 3. Breit-Wigner mass M_0 and width Γ_0 parameters obtained in a combined fit to DK and D^*K invariant mass distributions described in the text. The first error is statistical and the second is the systematic uncertainty, estimated from the variety of parameters obtained from fits to individual sub-systems and from variations in the selection criteria.

state	$M_0/(\mathrm{MeV}/c^2)$	$\Gamma_0/(\mathrm{MeV}/c^2))$
$D^*_{s1}(2710)$	$2710 \pm 2^{+12}_{-7}$	$149 \pm 7^{+39}_{-52}$
$D^*_{sJ}(2860)$	$2862 \pm 2\ ^{+5}_{-2}$	$48 \pm 3 \pm 6$
$D_{sJ}(3040)$	$3044 \pm 8^{+30}_{-5}$	$239 \pm 35^{+46}_{-42}$

the same in both systems and their spins to be, respectively, 1 and zero. The resulting masses and widths are summarized in Table 3.

These data were also used to determine the branching ratios $\Gamma(\mathrm{D^*K})/\Gamma(\mathrm{DK})$:

$$\mathrm{D}^*_{\mathrm{s1}}(2710):\ 0.91\pm0.13_{\mathrm{stat}}\pm0.12_{\mathrm{syst}},$$
$$\mathrm{D}^*_{\mathrm{sJ}}(2860):\ 1.10\pm0.15_{\mathrm{stat}}\pm0.19_{\mathrm{syst}}.$$

6 Summary and outlook

BABAR has reported four observations providing significant evidence for oscillations in the $\mathrm{D^0\overline{D^0}}$ system. The HFAG has included these, with other measurements of mixing observables by Belle, CDF and earlier experiments to estimate values for the underlying mixing parameters [7].

$$x=0.98^{+0.24}_{-0.26}\%,\quad y=(0.83\pm0.16)\%,$$
$$|q/p|=0.87^{+0.17}_{-0.15},\quad \phi_{\mathrm{M}}=-8.5^{+7.4\circ}_{-7.0},$$
$$\delta_{\mathrm{K}\pi}=26.4^{+9.6\circ}_{-9.9},\quad \delta_{\mathrm{K}\pi\pi}=14.8^{+20.2\circ}_{-22.1}.$$

The combined result indicates that mixing occurs with a significance in excess of 10 σ. There is, so far, no evidence for CPV.

These results may not, per se, provide evidence for NP, but the value for x is at the high end of SM estimates. The existence of mixing, however, and its more detailed study lay open the possiblity to observe CPV and NP in the future generation of experiments.

Our understanding of $\mathrm{D_s}$ spectroscopy is improved with the new results from BABAR, but significant questions remain. Why are the $\mathrm{D}^*_{\mathrm{s0}}(2317)$ and $\mathrm{D_{s1}}(2460)$ masses so low, if they are simply $\mathrm{c\bar{s}}$ members of the $L=1$ level, while the corresponding $\mathrm{c\bar{u}}$ and $\mathrm{c\bar{d}}$ states are not. Is the $\mathrm{D}^*_{\mathrm{s1}}(2710)$ the radial excitation of the $\mathrm{D}^*_{\mathrm{s}}(2112)$? What is the spin of the $\mathrm{D}^*_{\mathrm{sJ}}(2860)$ and where does it fit in?

In both charm mixing and in spectroscopy, the best results are yet to come from BABAR and from Belle. The answers to many of these questions, however, may have to await the results from LHCb, BES III, Panda and SuperB/Belle2.

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