Status of Wrong-Sign D^0 Decays

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In this note, we describe our progress so far in the analysis of wrong-sign D^0 decays, such as $D^0 \to K^+\pi^-$.

Primer

CLEO, with the detector in the CLEO-II configuration, obtained evidence for the wrong sign decay, $D^0 \to K^+\pi^-$:

$$R_{DK2} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = (7.7 \pm 2.5 \pm 2.5) \times 10^{-3} = (2.92 \pm 0.95 \pm 0.95) \tan^4 \theta_C \quad (1)$$

A closely related CLEO result is:

$$R_{DK3} = \frac{\Gamma(D^0 \to K^+\pi^-\pi^0)}{\Gamma(D^0 \to K^-\pi^+\pi^0)} < 6.8 \times 10^{-3} = 2.6 \tan^4 \theta_C \;\; (90\% \;\; \text{C.L.}) \quad (2)$$

Wrong sign decays can proceed either 'directly,' through an amplitude (call it B) that takes the D^0 directly to the wrong-sign final state, or through 'state-mixing' (a.k.a. 'mixing' or 'indirectly'), through an amplitude (call it M) that first takes the D^0 to a $\overline{D^0}$ intermediate state, and then takes the $\overline{D^0}$ to its own right-sign (but wrong-sign for the D^0) final state; let's call the amplitude for the right-sign transition of the $\overline{D^0}$, $\overline{A}$. In absence of 'direct CP violation', $|B| = |\overline{B}|$ and $|A| = |\overline{A}|$; final state interactions spoil the equalities if one removes the absolute values.

Qualitatively, the intermediate step in the mixing-induced amplitude suppresses that transition by a factor of $-it$, the time since birth of the D^0, relative to the direct amplitude: the $-i$ comes from the Schrodinger equation.

Assuming that wrong-sign decays are insignificant compared to the mean rate of decay in the $D^0 - \overline{D}^0$ system, $\overline{\Gamma} = 1/\tau_{D^0}$ (this assumption is actually not valid, given the current experimental limits on wrong-sign decays, a point which we address later), the wrong-sign decay rate, $w(t)$, is then approximately:

$$w(t) \approx |B - i\overline{A}Mt|^2 e^{-\overline{\Gamma}t} \quad (3)$$

$$\approx |\overline{A}|^2 \left[\left| \frac{B}{\overline{A}} \right|^2 + 2\mathrm{Im}\left[\frac{BM}{\overline{A}} \right] t + |M|^2 t^2 \right] e^{-\overline{\Gamma}t} \quad (4)$$

In Equation 4, the three terms, proportional to t^0, t^1, and t^2 respectively, are sometimes called 'DCSD' for Doubly Cabibbo Suppressed Decay (for hadronic final states), 'interference,' and 'mixing'. In the case of semileptonic final states, the terms proportional to t^0 and t^1 would be absent or very small. Some hairsplitting: we lack explicit proof that the wrong sign decays described by Equation 1 are due to DCSD, and the magnitude of the signal is a bit larger than the naive expectation of $\tan^4\theta_C$; the interference term *can be present in absence of CP violation*, if M has an imaginary part, as would occur from mixing through real intermediate states, or '$\Delta\Gamma$'; the first two terms are only absent for semileptonic decays if the $\Delta C = \Delta Q$ rule is valid, which is true in the Standard Model to first order.

A few points from physics: the naive expectation for $B/\overline{A}$ is $-\tan^2\theta_C$. The minus sign originates in the relative minus sign between the two off-diagonals of the Cabibbo matrix. Removing one layer of naivete: an enhancement of $|B/\overline{A}|$, which is both expected and measured, means that a strong-interaction phase shift between B and $\overline{A}$ is likely, so

$$\frac{B}{\overline{A}} = \rho e^{-i\delta_s}[-\tan^2\theta_C]. \tag{5}$$

Here, ρ is real, positive, and appears to have (for $K^{\mp}\pi^{\pm}$) a magnitude greater than one; both ρ and δ_s vary from hadronic final state to hadronic final state: those for $K\pi$ need not equal those for $K\pi\pi^0$, etc. The phase shift is important in obtaining the imaginary part of the interference term.

At the highest level of sophistication, one would include CP violation in $B/\overline{A}$, but we think that this is probably too sophisticated, and, in general below, we will ignore this possibility. Recently, E791 spent a lot of time on CP violation, but overlooked the simpler issue of a strong-interaction phase shift.

The 'DCSD' rate is sometimes parameterized, for hadronic final states, as:

$$r_{DCS} = r_{2C} = R_{\mathrm{DCSD}} \equiv \left|\frac{B}{\overline{A}}\right|^2 = \text{ (no direct CP violation) } \left|\frac{B}{A}\right|^2 = \rho^2\tan^4\theta_C. \tag{6}$$

This term depends on the decay mode used to measure it. Probably, a useful notation could be borrowed from Kaon physics: when $K\pi$ is the final state, call the relevant $|B/A|^2$ r_{DK2}, indicating that a D decayed to a K that carried the flavor information, and the decay was 2 body. So, r_{DK3} would be a 3 body decay, as would r_{De3}, etc.

The mixing amplitude, M, is written (in Kaon physics):

$$M = \frac{1}{2}\Delta M - \frac{i}{4}\Delta\Gamma = -\frac{i}{2}e^{-i\phi_{\mathrm{SW}}}\sqrt{\Delta M^2 + \frac{1}{4}\Delta\Gamma^2}, \tag{7}$$

where the 'superweak angle' ϕ_{SW} is defined as:

$$\phi_{\mathrm{SW}} = \tan^{-1}\left(-2\frac{\Delta M}{\Delta\Gamma}\right) \tag{8}$$

Here, most theoretical interest is in ΔM, because it is caused by mixing through transitions to intermediate states that have rest energies greater than that of the D^0, such as hypothetical

Table 1: Fixed Target Wrong-sign Results (all 10^{-3})

Experiment	r_{mix}	r_{DK2}	r_{DK4}
E691 (hadronic)	< 3.7 (90% C.L.)	< 15 (90% C.L.)	< 18 (90% C.L.)
E791 (hadronic)	< 3.3 (90% C.L.)	6.8 ± 3.3	2.5 ± 3.5
E615 (semileptonic)	< 5.6 (90% C.L.)		
E791 (semileptonic)	< 5.0 (90% C.L.)		

particles. The term $\Delta\Gamma$ involves sums over intermediate states that have rest energies lower than that of the D^0, such as KK, $\pi\pi$, $K\pi$, etc. The suggestion that $\Delta\Gamma$ is the more significant term is quite common in the literature: this would then mean that $\phi_{\rm SW} \approx 0$.

The mixing term, for all decay types, is sometimes parameterized (ignoring CP violation):

$$r = r_{mix} = r_M = R_{\rm mixing} \equiv 2\overline{\Gamma}^{-2}|M|^2 = \frac{1}{2}\left[\left(\frac{\Delta M}{\overline{\Gamma}}\right)^2 + \left(\frac{\Delta\Gamma}{2\overline{\Gamma}}\right)^2\right] = \frac{1}{2}[x^2 + y^2] \tag{9}$$

Where, $x \equiv \Delta M/\overline{\Gamma}$ and $y \equiv \Delta\Gamma/(2\overline{\Gamma})$; y is limited to the range -1 to 1, where 1(-1) would indicate that CP=+1(-1) states dominated the total width of the D^0. This term should be independent of the decay mode used to measure it.

From these many definitions, Eqn. 3 can be written in the fashion (dropping a $|\overline{A}|^2$ that is factored out):

$$w(t) = \left|-\sqrt{R_{\rm DCSD}}e^{-\delta_s} - \sqrt{\frac{R_{\rm mixing}}{2}}e^{-\phi_{\rm SW}}\tau\right|^2 \tag{10}$$

where $\tau = \overline{\Gamma}t$, and one can then obtain the interference term easily:

$$r_{int} = \sqrt{2R_{\rm DCSD}R_{\rm mixing}}\cos(\phi = \delta_s + \phi_{\rm SW}) \equiv 2{\rm Im}\left[\frac{BM}{\overline{A}\,\overline{\Gamma}}\right] \tag{11}$$

The CLEO results in Equations 1 and 2 were obtained without any use of information about the time of decay, and consequently the acceptance was flat in t, and so, CLEO measured the integral of $w(t)$.

Now that we have installed the silicon vertex detector, we can reconstruct the time of decay with a resolution of approximately $\tau_{D^0}/4$. So, we can in principle sort out which components of Equation 4 contribute to the result of Equation 1.

We have analyzed two fixed-target experiments that have sought wrong-sign hadronic final states. E691 and E791: their results are summarized in Table 1; we also show the results of two analyses of semileptonic final states. For those experiments, the acceptance was *not flat in t*, in distinction to the acceptance for CLEO. For E691, the acceptance was zero for $t < 0.53\tau_{D^0}$, and then turned on sharply, and increased linearly by about 50% to its asymptotic value at $t = 4.8\tau_{D^0}$. For E791, the acceptance rises linearly from 0 to about 50% at $t = \tau_{D^0}$, and then reaches its asymptotic value at about $t = 2\tau_{D^0}$.

Table 2: Comparison of Wrong-sign Sensitivities

Experiment (fb^{-1}, $p_{D^*} >$ GeV)	Mode	# RS 10^3 d:m	$\sigma_{\delta M}$ KeV	$B_{\rm WS}$ $\rm MeV^{-1}$	S/B ev. d:m	r - Sta. Err. 10^{-3} calc/act
C-II (1.8,3.1)	$K\pi$	2.2	770	5.3	17/16	1.8/2.5
C-II (2.5,2.9)	$K\pi\pi^0$	4.2	640	25	14/63	1.9/2.7
E791	$K\pi$	5.2:13.5	760	38	36/100:28/100	1.9/3.4:0.7/1.2
E791	$K3\pi$	3.5:9.7	760	16	9/43:20/43	1.9/3.5:0.7/1.2
C/SVX (3.8,3.1)	$K\pi$	2.8	250	6.7	22/7	0.9
C/SVX (3.8,2.9)	$K\pi\pi^0$	5.3	250	32	18/32	1.1
C/SVX (3.8,2.0)	$K\pi$	7.3	250	70	57/70	1.1
C/SVX (3.8,2.0)	$K\pi\pi^0$	10	250	240	34/240	1.5

The acceptance limitations in fixed target experiments are the result of their cuts to suppress background near $t = 0$. The cuts are less restrictive for E691 because their beam consists of photons, while the E791 beam consists of pions.

The fixed target acceptance limitations render them relatively *less* sensitive to direct $D^0 \to K^+\pi^-$ decays, which have a t^0 weighting in time, and relatively *more* sensitive to mixing in absence of interference, which has a t^2 weighting in time.

None of the three experiments, CLEO-II, E691, or E791, had a background-free situation. CLEO-II, in the result of Equation 1, was able to pull a signal out from from the background, *without* information on the $c\tau$ of the decay; E691 and E791 were unable to do so, even though they had $c\tau$ information. Qualitatively, this is because the e^+e^- environment has less background than the fixed-target environment.

Measurement of the $c\tau$ with the SVX should enable us to combine the low background advantage of CLEO-II with the advantages of the fixed target experiments, to achieve improved sensitivity to all types of wrong-sign D decay.

A simple study of the improvement possible *prior* to use of the $c\tau$ information from the SVX is summarized in Table 2. The improvements brought by the SVX in the resolution in δM, the $D^* - D$ mass difference, are included there. In senstivity to direct wrong sign decays, the SVX brings a factor of 2-3 in sensitivity, *prior* to $c\tau$ measurement. Exploitation of $c\tau$ may well bring another factor of 2.

The details that go into Table 2 follow. For the CLEO cases, the integrated luminosity is included in the first column; the CLEO/SVX numbers correspond to the data that we are likely to have processed by the end of 1997. For CLEO, the momentum cut on the D^* is stated as well; we are investigating lowering this cut, and the second set of C/SVX numbers reflect this change: we assume that the cost is an increase of a factor of 4 in background. The '# RS' column, for fixed target experiments, is *different*, depending upon whether a limit is being set on wrong sign final states from direct decay, or from mixing. Because of the difference between t^0 and the t^2 dependence of direct decay and mixing, respectively, the lifetime cut made by the fixed target experiments changes the relative acceptance for those processes, and we reflect this acceptance change in their effective number of right sign decays. The background under the wrong sign, $B_{\rm WS}$, is quoted in events per MeV on the δM plot, which is useful if the dominant background is a $\overline{D^0}$ and a random slow pion, as we expect at the moment. The rough breakdown of the number of events in a search region roughly 2σ in both M_D and δM coming from signal and background is shown.

Finally, the calculated error on the 'r' parameter, *assuming no signal*, is shown, as well as the actual statistical error quoted in the relevant publication. Only in the case of CLEO-II $K\pi$ have we been able to trace the origin of the discrepancy: it is the contribution to the statistical error by the *signal* seen in that case. In any case, it is always good to compare apples with apples, which is why we compute the statistical error in the same manner for all the different searches.