Searches for D^0 - $\bar{D}^0$ Mixing, Rare Charm and Tau Decays¹

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Abstract. I discuss the results on D^0 - $\bar{D}^0$ mixing through hadronic as well as semi-leptonic charm decays, rare flavor-changing neutral currents in the charm sector and the lepton flavor violating τ decaying to charged lighter leptons. The results from both *BABAR* and *Belle* are presented in this review.

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D^0 - $\bar{D}^0$ MIXING VIA $D^0 \rightarrow K^+\pi^-\pi^0, K^+\pi^-$ AND $K^{(*)-}e^+\nu$

The mixing in the charm sector, namely $D^0 - \bar{D}^0$ mixing has received less attention in the past because of very small Standard Model (SM) expectations. However, it is the GIM (Glashow, Iliopoulos and Maiani) mechanism that makes the charm mixing so interesting. At small distances, this mixing proceeds via flavor-changing neutral currents (FCNC). Since there are no tree-level FCNC contributions in the SM, processes such as mixing occur at the quark level primarily via box diagrams. The exact evaluation of box diagram is not so important because $D^0 - \bar{D}^0$ mixing is probably dominated by long distance effects [1], i.e., by intermediate hadronic states (not quarks) in the $D^0 - \bar{D}^0$ transition.

The mixing processes are parameterized with the quantities x and y where

$$x \equiv 2 \frac{m_2 - m_1}{\Gamma_2 + \Gamma_1}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1}. \quad (1)$$

(m_1, m_2) and (Γ_1, Γ_2) are the mass and decay widths of mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ (p and q are complex numbers). If x and $|y|$ are very small, then D^0 and $\bar{D}^0$ practically do not oscillate into and from each other while decaying; the linear superposition at the production time is identical with the one at the decay time.

The first search for D mixing in the decay $D^0 \rightarrow K^+\pi^-\pi^0$, which is wrong sign (WS) decay, is presented here. For a nonleptonic multibody WS decay, the time dependent decay rate, $\Gamma_{WS}(t)$, relative to a corresponding right-sign (RS) rate, $\Gamma_{RS}(t)$, is approximated by [2]

$$\frac{\Gamma_{WS}(t)}{\Gamma_{RS}(t)} = \tilde{R}_D + \alpha \tilde{y}' \sqrt{\tilde{R}_D} (\Gamma t) + \frac{\tilde{x}'^2 + \tilde{y}'^2}{4} (\Gamma t)^2 \quad (2)$$

$$0 \leq \alpha \leq 1.$$

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The tilde indicates quantities that have been integrated over any choice of phase-space regions. $\tilde{R}_D$ is the integrated doubly Cabibbo suppressed (DCS) branching ratio, $\tilde{y}' = y \cos \tilde{\delta} - x \sin \tilde{\delta}$ and $\tilde{x}' = x \cos \tilde{\delta} + y \sin \tilde{\delta}$, where $\tilde{\delta}$ is an integrated strong-phase difference between the Cabibbo favored (CF) and the DCS decay amplitudes, α is a suppression factor that accounts for strong-phase variation over the phase space regions, and Γ is the average width. The time-integrated mixing rate $R_M = (\tilde{x}'^2 + \tilde{y}'^2)/2 = (x^2 + y^2)/2$ is independent of decay mode. The CP -violating effects are studied by fitting to the $D^0 \rightarrow K^+ \pi^- \pi^0$ and $\bar{D}^0 \rightarrow K^- \pi^+ \pi^0$ samples separately. The CP -violation in the interference between the DCS channel and mixing, parameterized by an integrated CP -violating-phase difference $\tilde{\phi}$, as well as CP violation in mixing, parameterized by $|p/q|$. The CP invariance in the DCS and CF decay rates is assumed.

Assuming CP conservation, using 230.4 fb^{-1} *BABAR* measured the time-integrated mixing rate $R_M = (0.023^{+0.018}_{-0.014} \text{ (stat.)} \pm 0.004 \text{ (syst.)})\%$, and $R_M < 0.054\%$ at the 95% confidence level [3]. The data is consistent with no mixing at the 4.5% confidence level (C.L). Considering the entire allowed phase space, the branching ratio for WS decay relative to RS decay is $(0.214 \pm 0.008 \text{ (stat.)} \pm 0.008 \text{ (syst.)})\%$.

Belle searched for D^0 - $\bar{D}^0$ mixing in WS decay $D^0 \rightarrow K^+ \pi^-$ based on 400 fb^{-1} of data [4]. Assuming CP conservation, *Belle* finds $x'^2 < 0.72 \times 10^{-3}$ and $-9.9 \times 10^{-3} < y' < 6.8 \times 10^{-3}$ at the 95% C.L. The no-mixing point (0,0) has a confidence level of 3.9%. Assuming no mixing, $R_D = (0.377 \pm 0.008 \pm 0.005)\%$. Also *Belle* searched for mixing in the neutral D meson system using semileptonic $D^0 \rightarrow K^{(*)-} e^+ \nu$ decays using 253 fb^{-1} of data [5]. Neutral D mesons from $D^{*+} \rightarrow D^0 \pi^+$ decays are used; the flavor at production is tagged by the charge of the slow pion. From the yield of RS and WS decays arising from non-mixed and mixed events, respectively, the upper limit (UL) of the time-integrated mixing rate is $R_M < 1.0 \times 10^{-3}$ at 90% C.L.

MEASUREMENT OF THE PSEUDOSCALAR DECAY CONSTANT f_{D_s} USING CHARM-TAGGED EVENTS

Measurements of pure leptonic decays of charmed pseudoscalar mesons are of particular theoretical importance. They provide an unambiguous determination of the overlap of the wavefunctions of the heavy and light quarks within the meson, represented by a single decay constant (f_M) for each meson species (M). The partial width for a D_s^+ meson to decay to a single lepton flavor (l) and its accompanying neutrino (ν_l), is given by

$$\Gamma(D_s^+ \rightarrow l^+ \nu_l) = \frac{G_F^2 |V_{cs}|^2}{8\pi} f_{D_s}^2 m_l^2 m_{D_s} \left(1 - \frac{m_l^2}{m_{D_s}^2}\right)^2, \quad (3)$$

where m_{D_s} and m_l are the D_s^+ and lepton masses, respectively, G_F is the Fermi constant, and V_{cs} is the CKM matrix element giving the coupling of the weak charged current to the c and s quarks. In order to measure $D_s^+ \rightarrow \mu^+ \nu_\mu$, the decay chain $D_s^{*+} \rightarrow \gamma D_s^+, D_s^+ \rightarrow \mu^+ \nu_\mu$ is reconstructed from D_s^{*+} mesons produced in the hard fragmentation of continuum $c\bar{c}$ events. The branching fraction of $D_s^+ \rightarrow \mu^+ \nu_\mu$ cannot be determined directly, since the production rate of $D_s^{(*)+}$ mesons in $c\bar{c}$ fragmentation is unknown. Instead the partial width

ratio $\Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu)/\Gamma(D_s^+ \rightarrow \phi \pi^+)$ is measured by reconstructing $D_s^{*+} \rightarrow \gamma D_s^+ \rightarrow \gamma \phi \pi^+$ decays. The $D_s^+ \rightarrow \mu^+ \nu_\mu$ branching fraction is evaluated using the measured branching fraction for $D_s^+ \rightarrow \phi \pi^+$. Using the *BABAR* average for the branching ratio $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+) = (4.71 \pm 0.46)\%$ [6] [7], we obtain the branching fraction $\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (6.74 \pm 0.83 \pm 0.26 \pm 0.66) \times 10^{-3}$ and the decay constant $f_{D_s} = (283 \pm 17 \pm 7 \pm 14) \text{ MeV}$. The first and second errors are statistical and systematic, respectively; the third is the uncertainty from $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+)$. Using $\mathcal{B}(D_s^+ \rightarrow \phi \pi^+)_{\text{PDG}} = (3.6 \pm 0.9)\%$ [8], the branching fraction is $\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (5.15 \pm 0.63 \pm 0.20 \pm 1.29) \times 10^{-3}$ and the decay constant $f_{D_s} = (248 \pm 15 \pm 6 \pm 31) \text{ MeV}$ [9].

SEARCH FOR FLAVOR-CHANGING NEUTRAL-CURRENT CHARM DECAYS

As mentioned earlier, in SM, FCNC processes cannot occur at the tree level. It therefore provides an excellent tool for investigating the quantum corrections in the SM as a way to search for evidence of physics beyond the SM. FCNC processes have been studied extensively for K and B mesons in $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing processes and in rare FCNC decays, such as $s \rightarrow d \ell^+ \ell^-$, $b \rightarrow s \gamma$ and $b \rightarrow s \ell^+ \ell^-$ decays. The present measurements of these processes agree with SM predictions [10], but there are strong ongoing efforts to improve both the measurements and the theoretical predictions, and to measure new effects, such as CP violation, in FCNC processes. In the SM very small signals are expected, as a consequence of effective GIM cancellation. This contribution is masked by the presence of long-distance contributions from intermediate vector resonances. *BABAR* searched for rare FCNC charm decays of the form $X_c^+ \rightarrow h^+ \ell^+ \ell'^-$, where X_c^+ is a charm hadron, h is a pion, kaon or proton, and $\ell^{(\prime)}$ is an electron or a muon. In the pion and kaon modes, both D^+ and D_s^+ decays are studied, while in the proton modes Λ_c^+ decays are studied. Based on a data sample of 288 fb^{-1} , the ULs on the branching fractions of the different decay modes at 90% C.L are set in the range $(4 - 40) \times 10^{-6}$ [11].

LEPTON FLAVOR VIOLATION IN TAU DECAYS

The observation of the neutrino oscillation implies that the lepton flavor is not individually conserved. Therefore lepton-flavor-violating (LFV) processes in the charged-lepton sector are allowed. In simple extensions to SM, which accomodate mixing of massive neutrinos, the rate of the LFV processes is accompanied by large suppression and is far out of the reach of the experimental detection. On the other hand, several SUSY models [12] predict LNV tau decay rates up to and above the present experimental limits, making that physics channel one of the most sensitive probes for low-energy SUSY searches.

The results for lepton flavor violating decays $\tau \rightarrow l x$ where l is either electron or muon, and x is γ , K_S^0 , hh (h is light charged hadrons: kaon or pion) or V^0 (a neutral vector mesons such as ρ^0 , $K^*(892)^0$, ϕ) are discussed in this section. *BABAR* and Belle searched for the above mentioned LFV tau decays in tau pairs produced from e+e- collisions around the $Y(4s)$ peak.

In the typical analysis, the plane perpendicular to the thrust axis is used to divide each event in two hemispheres containing a candidate SM tau decay (tag-side) and a LFV tau decay (signal-side), respectively. Background events are suppressed with requirements on the missing mass, momentum or energy of the event, due to the neutrino(s) in the SM tau decay. Signal events are selected by requiring that the candidate decay products total energy is compatible with the tau energy in the center-of-mass (C.M.) system (half the total C.M. energy) and that their invariant mass is compatible with the tau mass within the experimental resolution.

Using data corresponding to an integrated luminosity of 232 fb^{-1} *BABAR* measures the UL on branching fraction, $\mathcal{B}(\tau^- \rightarrow \mu^- \gamma) < 6.8 \times 10^{-8}$ [13] and $\mathcal{B}(\tau^- \rightarrow e^- \gamma) < 1.1 \times 10^{-7}$ [14] at the 90% C.L. Using the results from $\tau^- \rightarrow \mu^- \gamma$ one can constrain the parameter space in $\tan\beta - m_A$ plane, where $\tan\beta$ is the ratio of vacuum expectation values of the two Higgs doublets and the m_A is the CP conserving Higgs boson mass, and the current result excludes the higher $\tan\beta$ region.

Belle searched for the lepton flavor violating decays $\tau^- \rightarrow l^- K_S^0$ ($l = \mu, e$) using 281 fb^{-1} data and set the UL to be less than 4.9×10^{-8} and 5.6×10^{-8} at the 90% C.L. for muon and electron modes, respectively [15]. For $\tau^- \rightarrow lhh$ or $\tau^- \rightarrow lV^0$ modes [16], with 158 fb^{-1} data, Belle set 90% C.L. upper limits for the branching fractions in the range of $(1.6 - 8.0) \times 10^{-7}$ at the 90% C.L. For $\tau^- \rightarrow lhh$ decay, using 221 fb^{-1} data, *BABAR* set upper limits in the range of $(0.7 - 4.8) \times 10^{-7}$ at 90% C.L. [17].

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