D⁰–D̅⁰ Mixing and Rare Decays of the D⁰ and D⁺

Sean McHugh
University of California, Department of Physics, Santa Barbara, CA. 93106, USA

We present a limit on D⁰ – D̅⁰ mixing from E691 that r_m < 0.0037 at the 90% confidence level where r_m is the ratio of wrong sign decays from mixing to right sign decays. Limits on doubly Cabibbo suppressed decays of the D⁰ are given. Results on mixing from ARGUS and MARK III are also discussed. Upper limits for several rare D⁰ decays are below 4 × 10⁻⁵. New limits below 10⁻³ for several rare D⁺ decays are presented.

1. D⁰–D̅⁰ Mixing

As in the neutral kaon system, mixing of particle and antiparticle states can occur in the D⁰ – D̅⁰ system. The two systems differ because of the short lifetime and large mass of the charmed quark in the D⁰. Standard model calculations¹ based on the box diagram predict mixing of the D⁰ system to be at a rate of less than 10⁻⁴. However, long range and other effects²,³ could allow a higher rate of mixing to about 0.5%. Extensions to the standard model⁴,⁵ can predict rates as high as 1–2%. Therefore the observation of mixing at the level of a few percent would be an indication of new physics. In this paper recent upper limits on the rate of D⁰ – D̅⁰ mixing are discussed.

The experimental quantity r is defined to be the the ratio of branching fractions of a D⁰ decaying to a final state of strangeness +1 (wrong sign decay) to that of the usual decay to a final state of strangeness –1 (right sign decay). The signature for mixing is complicated by the possibility of doubly Cabibbo suppressed decay (DCSD) which also leads to a wrong sign final state. A simplified formula⁶ for the rate of the D⁰ going into a wrong sign final state is given by

\[ N(D^0 \rightarrow \text{wrong sign}) = \frac{e^{-\Gamma t}}{4} \left[ t^2(\Delta M)^2 + 4|\rho|^2 \right] \] (1)

where the term proportional to t² is due to mixing and the second term due to DCSD. Here \( \Gamma \) is the D⁰ width, \( \Delta M \) is the mass shift between the CP eigenstates and the term proportional to \( |\rho|^2 \) is the DCSD contribution. This formula is valid in the limit where CP violation is ignored and \( \Delta M \gg \Delta \Gamma \). The magnitude of the DCSD contribution is expected to be on the order of \( \tan^4 \theta_c \) or about 0.3%.

There is a hint of mixing from MARK III.⁷ While observing e⁺e⁻ collisions at the energy of the \( \psi''(3770) \), which decays to a D⁰D̅⁰ pair exclusively, they completely reconstructed 224 events. Of these they found three events in which the total...
strangeness is 2. From Monte Carlo studies they expect only about one event due to DCSD and background. This event rate implies that $r \sim 1\%$.

Fermilab photoproduction E691$^{[8,9]}$ has used its fine resolution Silicon Microstrip Detector (SMD) and the Tagged Photon Spectrometer to look for mixing. The precise spatial resolution of the SMD allows them to obtain very clean and large samples of charmed particles through the decays $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ [K^- \pi^+]$ and $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ [K^- \pi^+ \pi^- \pi^+]$ and their charm conjugates. Also they use the pion of the $D^{*+}$ decay to tag the charm quantum number ($D^0$ or $\bar{D}^0$) at production. They then search for $D^*$ events which have the wrong sign, that is, the wrong combination of charge and strangeness. In the $K\pi$ case this is $D^{*+} \rightarrow D^0 \pi^+ \rightarrow [K^+ \pi^-] \pi^+$ and its charge conjugate. Finally, the time dependence given in (1) is exploited to separate mixing from DCSD and thus define $r_m$, $r$ due to mixing alone. A cut at two $D^0$ lifetimes, for example, retains 68% of all mixing event yet only 14% of the DCSD.

As an illustration only, Fig. 1 shows two scatter plots of the invariant $K\pi$ mass versus the $Q$ value defined as $Q = M_{K\pi} - M_{K\pi} - M_{\pi}$. The upper and lower plots are for right sign and wrong sign decays respectively. The expected signal regions are delimited by the boxes shown in the figure. A cut on the measured lifetime of the $D^0$ has been made at 0.22 ps. There are 611 counts within the boxed region of Fig. 1(a). Figure 2 shows the same scatter plots with a lifetime cut of 0.88 ps (approximately two $D^0$ lifetimes). With this cut there should be 2.7 background events if there is no mixing. There is just one event in the signal region. If $r_m \sim 1\%$ then there would be about 11 events within the box.

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Fig 1(a) The scatter plot of $Q$ versus $M(K\pi)$ for $(K^- \pi^+)\pi^+$ events, with the requirement $t > 0.22$ ps. (b) The plot for $(K^- \pi^+)\pi^-$ events with $t > 0.22$ ps

Fig 2(a) The scatter plot of $Q$ versus $M(K\pi)$ for $(K^- \pi^+)\pi^+$ events, with the requirement $t > 0.88$ ps. (b) The plot for $(K^- \pi^+)\pi^-$ events with $t > 0.88$ ps