Charged D^* Production in e^+e^- Annihilation at 29 GeV and a Limit on D^0-$\bar{D}^0$ Mixing

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We have studied inclusive $D^{*\pm}$ production using the DELCO detector at PEP. Our technique involved kaon identification in the momentum range above 3.2 GeV/c using a threshold gas Čerenkov counter. This leads to a model-independent upper limit on D^0-$\bar{D}^0$ mixing of 8.1% (90% confidence level). We also have measured the charm fragmentation function, which peaks at $x \equiv P_{D^*}/(E_{\rm beam}^2 - M_{D^*}^2)^{1/2}$ of 0.56 ± 0.06(stat.), and the total cross section for D^* production, $\sigma(D^{*\pm}) = 0.140 \pm 0.021(\text{stat.}) \pm 0.032(\text{syst.})$ nb ($x > 0.3$, with radiative correction).

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In the standard model of weak and electromagnetic interactions with one Higgs doublet and six quarks, flavor-changing neutral currents are absent and the rate of D^0-$\bar{D}^0$ mixing is expected to be negligible.[1] Thus, the observation of mixing at the percent level would present a serious difficulty for the standard model. In this paper we report a measurement of D^* production with the DELCO detector using the kaon identification capability of the Čerenkov counter. This provides a unique way of checking the background and also leads to an upper limit on D^0-$\bar{D}^0$ mixing. The data were collected at the Stanford Linear Accelerator Center storage ring PEP at a c.m. energy of 29 GeV. The total data sample consists of 45 508 hadronic events, corresponding to an integrated luminosity of 150 ± 10 pb^{-1}.

The low Q value of the decay mode $D^{*+} \rightarrow D^0\pi^+$ (and its charge conjugate) has been exploited extensively to identify it in various experiments.[2-6] At the storage rings PEP and PETRA, several experiments have yielded measurements of D^* production with this technique[4] but with little or no particle identification.

The D^0-$\bar{D}^0$ mixing is studied[2] in the decay $D^{*+} \rightarrow D^0\pi^+$, and $D^0 \rightarrow K^-X^+$, where X is usually a single pion. The pion from the D^* carries the charge of the D^*, and the charge of the kaon indicates the charm quantum number of the D^0 (or $\bar{D}^0$) at the time of its decay. Thus a transition $D^0 \rightarrow \bar{D}^0$ would result in a "wrong sign" (i.e., same sign) combination of the kaon and the pion from the D^* decay.

The main feature of the detector pertinent to this measurement is a 36-cell Čerenkov counter,[7] which covers 60% of 4π. This counter is located between sixteen layers of inner drift chambers and six layers of outer drift chambers. The momentum resolution of the detector σ_P/P is $[(0.02P)^2 + 0.06^2]^{1/2}$, where P is measured in GeV/c.

Kaons with momentum above 9.3 GeV/c give a signal in the Čerenkov counter, while the pion threshold is at 2.6 GeV/c. Therefore, a track is identified as a kaon candidate when its momentum is sufficiently above pion threshold (a 3.2-GeV/c cut is used) and the Čerenkov cell it traverses does not give a signal. This remains true even when there are other tracks in the same cell. The kaon sample selected this way contains about 30% protons, which increase the random background in the D^* sample. The pion contamination is mostly due to momentum mismeasurements, which cause pions below its threshold to be found well above the threshold, and is estimated to be 5% of the kaon sample.

A D^0 candidate consists of a kaon candidate and any other track of opposite charge (assumed to be a pion) where the cosine of the opening angle between the two tracks is greater than 0.4 and the pair mass is between 1.45 GeV/c^2 and 2.2 GeV/c^2. Each D^0 candidate is constrained[8] to the nominal mass 1.8647 GeV/c^2 by adjustment of its energy and then combined with each of the remaining tracks in the D^0 hemisphere (assumed to be pions), and the mass difference $\Delta M \equiv M_{D^0\pi} - M_{D^0}$ is calculated. The low Q value of the D^* decay, 5.8 MeV, makes the D^0 and the decay pion nearly collinear. Figure 1 is a scatter plot of ΔM versus the sine of the angle between the D^0 candidate and the second pion, $\sin\theta_{D^0\pi}$, for (a) right-sign and

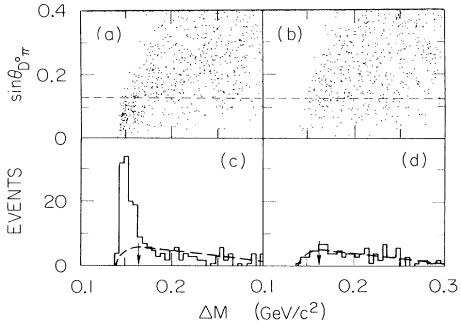

FIG. 1. The mass difference ΔM vs $\sin\theta_{D^0\pi}$ for (a) the right-sign and (b) the wrong-sign combinations of K and the second π. The projections of the corresponding scatter plots after an opening-angle cut $\sin\theta_{D^0\pi} < 0.13$ are shown in (c) and (d), where the dashed lines are the Monte Carlo estimated combinatorial background. The arrows indicate the ΔM cuts.

(b) wrong-sign combinations of the K and the second pion. A clear enhancement is seen in Fig. 1(a) in the region of low ΔM and small $\sin\theta_{D^0\pi}$. Figures 1(c) and 1(d) show the ΔM distributions after applying a cut of $\sin\theta_{D^0\pi} < 0.13$. We define the D^* signal region as $\Delta M < 0.1625$ GeV/c^2 and $\sin\theta_{D^0\pi} < 0.13$. There are 101 right-sign and 16 wrong-sign events in this region.

In order to estimate the amount of D^0-$\bar{D}^0$ mixing in the data, the number of wrong-sign combinations expected in the absence of mixing has to be determined. There are two major sources: the random combinatorial background and the Cabbibo-suppressed decay modes of D^0. Other possible sources, including the doubly Cabbibo-suppressed decay and kaon misidentifications, are small enough to be ignored. The background from the latter is small because the misidentifications are due to gross momentum mismeasurements, which tend to push the events outside the signal region. The combinatorial background shape is estimated from a large sample of events generated by the Lund jet Monte Carlo program,[9] which is put through detector simulation and the same selection criteria as described above, where genuine D^* combinations are eliminated. By normalization of the background shape for $\Delta M > 0.2$ GeV/c^2 in Fig. 1(d), the combinatorial background in the wrong-sign sample is estimated to be 18.1 events. Among the Cabbibo-suppressed decay modes of D^0, only the K^-K^+ mode makes a significant contribution. The detection efficiencies for other Cabbibo-suppressed modes are found to be small because of a mass misassignment and/or higher-multiplicity decay modes. The ratio $B(D^0 \to K^-K^+)/B(D^0 \to K^-\pi^+)$ is taken to be 0.12.[10] The estimated number of events in the wrong-sign sample from this source is 2.1, giving a total estimated wrong-sign background of 20.2 events.

A binomial distribution is used for the likelihood function, which leads to an upper limit on the D^0-$\bar{D}^0$ mixing rate r of 6.8% (90% confidence level), where r is defined to be the probability that a particle generated as D^0 decays as $\bar{D}^0$. In the presence of CP nonconservation, the rate of the $D^0 \to \bar{D}^0$ transition is not necessarily the same as the rate of $\bar{D}^0 \to D^0$. In such a case our experimental limit refers to an average mixing rate.

The systematic error in the estimated wrong-sign background due to the uncertainties in the background shape and the contribution from Cabbibo-suppressed D^0 decay modes is estimated to be 4 events. This raises the upper limit on r from 6.8% to 8.1%. This result is insensitive to the specific choice of cuts.

The current best upper limit on D^0-$\bar{D}^0$ mixing is 4.4%[11] and comes from a measurement of wrong-sign double-muon production in pion and proton interactions with iron. However, the inclusive nature of the experiment requires a set of assumptions on the cross section[12] and mechanism[13] of D^0 production. In contrast, D^{*+} decays provide a model-independent method of studying D^0-$\bar{D}^0$ mixing.

The mixing rate can be expressed[1] in terms of the masses m_i and decay widths Γ_i of the two mass eigenstates of the D^0-$\bar{D}^0$ system (assuming CP invariance):

$$r = \tfrac{1}{2}(\Gamma_-^2 + \delta m^2)/(\Gamma_+^2 + \delta m^2),$$

where $\Gamma_\pm = |\Gamma_1 \pm \Gamma_2|/2$, and $\delta m = |m_1 - m_2|$. Our limit of 8.1% on r gives the limits on the ratios, $\Gamma_-/\Gamma_+ < 0.40$ and $\delta m/\Gamma_+ < 0.44$. Also, the upper limit on r leads to a stringent limit on charm-changing neutral currents[14] of the type $g_L \bar{c}\gamma_\mu \frac{1}{2}(1-\gamma_5)u$, restricting the strength of the coupling constant g_L to be less than 1.6×10^{-3}.

We have determined the D^* production cross sections using the same data. In this analysis we assume that D^0-$\bar{D}^0$ mixing is small. Then the number of wrong-sign events can be subtracted from right-sign events in each momentum bin to yield the rate corresponding to the Cabbibo-favored charged K modes. The efficiency for observing the decay $D^{*+} \to D^0\pi^+$ has been estimated in each bin from the Monte Carlo analysis and corrected for the differences in tracking efficiency between the data and the Monte Carlo program.

The $K\pi$ mass resolution of the detector is not sufficient to distinguish the various D^0 decay modes. The relative fractions of D^0 decay modes that contribute to the D^* signal are estimated by the Monte Carlo analysis described above[15,16] and found to be 45% $K^-\pi^+$, 27% $K^-\pi^+\pi^0$, and 28% of other modes with a charged K, while the contribution from modes with no charged K is negligible.

We do not detect all the decay products of D^0 except in the $K^-\pi^+$ decay mode. Thus when the $K\pi$ mass is measured lower than the nominal D^0 mass, the apparent D^* momentum is systematically shifted lower than the real value, distorting the momentum distribution. In order to take this into account, the measured D^* momentum is multiplied by a correction factor which is a function of the measured $K\pi$ mass. The correction is estimated by the Monte Carlo analysis and is largest at the lower edge of the $K\pi$ mass range where the factor is 1.21. This correction makes the shape of the differential cross section insensitive to the relative D^0 branching ratios.

In Fig. 2(a) the resulting $D^{*\pm}$ cross section is shown as a function of $x \equiv P_{D^*}/P_{\max}$, where $P_{\max} = (E_{\text{beam}}^2 - M_{D^*}^2)^{1/2}$. Following Ref. 3, we have chosen this definition of x over E_{D^*}/E_{beam}, which has been used more frequently, in order to compare our measurements with data taken at different c.m. energies. The errors shown are statistical only. The points from other experiments[4] are overplotted for comparison. The fit to our data of the shape suggested by Peterson *et al.*[17] for the heavy-quark fragmentation function gives the single parameter $\epsilon = 0.36^{+0.14}_{-0.10}$, which corresponds to the peak position $x_{\max} = 0.56 \pm 0.06$. This suggests harder fragmentation for charm quarks than for light quarks and agrees qualitatively with other experiments. Our value of ϵ is consistent with $\epsilon = 0.41^{+0.10}_{-0.08}$ obtained by the HRS group[5] but slightly greater (i.e., softer fragmentation function) than the other measurements in the energy range of PEP and PETRA.

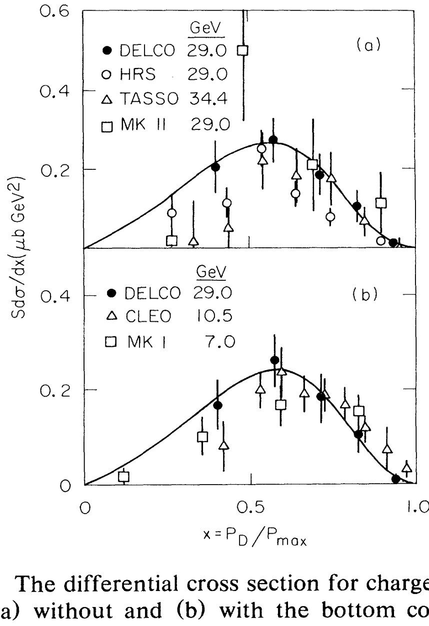

FIG. 2. The differential cross section for charged D^* production (a) without and (b) with the bottom contribution subtracted. All points are normalized to $B(D^{*+} \to D^0\pi^+) = 64\%$ and $B(D^0 \to K^-\pi^+) = 3.0\%$. The MARK I points are averages of D^0 and $D^\pm$ cross sections (Ref. 18), where the latter is normalized to $B(D^+ \to K^-\pi^+\pi^+)$ of 4.6%. The curves are the results of fits to our data of a shape suggested in Ref. 17.

We estimate that $(8 \pm 2)\%$ of the D^*'s in the acceptance are from b quarks. In order to compare our data with measurements at lower energies, the estimated bottom contribution has been subtracted in each bin. The results are compared with measurements at c.m. energies of 10.5 GeV (CLEO)[3] and 7.0 GeV (MARK I)[18] in Fig. 2(b). Again, fitting the shape of Ref. 17 to our data gives $\epsilon = 0.31^{+0.10}_{-0.08}$. The effect of the bottom subtraction on our data is small, and the qualitative agreement with lower-energy data is good.

The total cross section for $x > 0.3$ is measured to be $0.140 \pm 0.021(\text{stat.}) \pm 0.032(\text{syst.})$ nb. The systematic error includes the uncertainty in the detection efficiency and luminosity but not the uncertainty in the branching ratios. Since the neutral partner of $D^{*\pm}$ is expected from isospin symmetry to be produced in the same amount, the total D^* production inferred from our measurement is $0.280 \pm 0.042 \pm 0.064$ nb $(x > 0.3)$. The comparison of this value with the total cross section for charm production of 0.24 nb $(x > 0.3)$[19] (without bottom decays) indicates that D^* production dominates the known charm source. This is in agreement with the more direct measurements of the D^*/D production ratio by the HRS[5] and the CLEO[3] experiments. However, recent measurements by the MARK III group[20] suggest that the charged-K branching fractions of D^0 may be higher than the previously published values. If so, our measurement still could be consistent with pseudoscalar charmed mesons being directly produced as frequently as their vector partners.

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[8] The final signal-to-noise ratio is insensitive to this mass constraint.

[9] T. Sjostrand, Comput. Phys. Commun. **27**, 243 (1982), and **28**, 229 (1983).

[10] $B(K^-K^+)/B(K^-\pi^+)$ is $(11.3 \pm 3.0)\%$ according to R. H. Schindler *et al.* [Phys. Rev. D **24**, 78 (1981)] and $(12.5 \pm 1.8 \pm 1.0)\%$ according to R. H. Schindler [California Institute of Technology Report No. CALT-68-1161 (unpublished)]. We take an average of these two values to get $(12.1 \pm 1.7)\%$.

[11] A. Bodek *et al.*, Phys. Lett. **113B**, 82 (1982).

[12] The assumptions made are the following: (1) the dimuon sample is dominated by charm decays, and (2) the decay $D^0 \rightarrow \mu X$ accounts for 23% of the muons from charm decays.

[13] It was assumed that charm particle pairs are created incoherently. However, if D^0-$\bar{D}^0$ pairs are produced in a $C = -$ state (which is the case for Ψ'' decays) then the fraction of same-sign di-muons could be half that expected for incoherent cases. Thus, the larger the fraction of D^0's from such production modes, the higher the upper limit on D^0-$\bar{D}^0$ mixing should be. See R. L. Kingsley, Phys. Lett. **63B**, 329 (1976), or I. I. Bigi and A. I. Sanda, Nucl. Phys. **B193**, 85 (1981).

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[15] Schindler *et al.*, Ref. 10.

[16] The D^0 branching ratios used are 3.0% $K^-\pi^+$, 9.3% $K^-\pi^+\pi^0$, and 37% other K^- modes. $K^-\pi^+\pi^0$ is mostly produced as $K^-\rho^+$ and the polarization effect of the ρ is also simulated. G. G. Wohl *et al.* (Particle Data Group), Rev. Mod. Phys. **56**, No. 2, Pt. 2, S1 (1984), and Ref. 15.

[17] C. Peterson *et al.*, Phys. Rev. D **27**, 105 (1983), suggest $D(x) = x^{-1}[1 - 1/x - \epsilon/(1-x)]^{-2}$, where ϵ is related to the peak position $x_{\max}$ by $\epsilon = x_{\max} + 1/x_{\max} - 2$.

[18] P. A. Rapidis *et al.*, Phys. Lett. **84B**, 507 (1979).

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[20] Schindler, Ref. 10, reports $(4.9 \pm 0.9 \pm 0.5)\%$ for the $K^-\pi^+$ decay mode. Also, in Proceedings of the Twenty-Second International Conference on High-Energy Physics, Leipzig, July 1984 (to be published).