Inclusive Studies of D-Meson Decays at the $\psi(3772)$

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We have measured charged multiplicities, inclusive branching ratios to states containing kaons, and average energy fractions in charged and neutral particles for decays of D mesons produced at the $\psi(3772)$ resonance. The average charged multiplicity is 2.3 ± 0.3 for both the neutral and the charged D. We find inclusive branching ratios $B(D^0 \rightarrow K^{\pm}X) = 0.35 \pm 0.10$ and $B(D^+ \rightarrow K^- X) = 0.10 \pm 0.07$ for decays into charged kaons.

In previous papers we have reported measurements of branching ratios for several exclusive hadronic decay channels of the D mesons[1-2] and for inclusive semileptonic decays.[3] These decay modes account for only a fraction of all D-meson decays. The remaining modes are difficult to detect because of low acceptances and/or large backgrounds. Much can be learned, however, through inclusive studies of the final states in D decays. In this paper we report measurements of charged multiplicity distributions, inclusive branching ratios to states containing kaons, and the fraction of energy carried by charged and neutral particles in D^0 and $D^{\pm}$ decays.

The $\psi(3772)$ resonance,[4] recently discovered at SPEAR, lies just above the threshold for production of a pair of D mesons. The only allowed decay modes which contain charmed particles are $D^0\bar{D}^0$ and D^+D^-. Therefore, if a D^0 (D^+) is observed in an e^+e^- annihilation event at the $\psi(3772)$, the remaining particles in the event must be decay products of the $\bar{D}^0$ (D^-). Thus, these "tagged" events permit inclusive studies of the decays of D mesons.[5]

The data were collected with the Stanford Linear Accelerator Center–Lawrence Berkely Laboratory magnetic detector at SPEAR.[6,7] The $K^-\pi^+$ decay mode was used to tag $D^0\bar{D}^0$ events and the $K^-\pi^+\pi^+$ decay mode was used to tag D^+D^- events. (All references to a specific charge state also refer to the charge-conjugate state.) These two decay modes are the only ones which have a sufficiently small background and a sufficiently large acceptance in the magnetic detector for our study. The analysis techniques used to extract both samples are similar to those described previously.[1] The mass spectra can be found in Ref. 1. We find 141 $D^0 \rightarrow K^-\pi^+$ events and 107 $D^+ \rightarrow K^-\pi^+\pi^+$ events in ±8-MeV bands about the D^0 and D^+ masses. We estimate the background by extrapolating from the 1.75–1.85-GeV mass region to the signal region. We find expected backgrounds of 22 ± 2 D^0 events and 27 ± 2 $D^{\pm}$ events.

The charged multiplicity distributions for the decays of the recoil D's are obtained by simply counting the number of additional tracks in each event. Background multiplicity distribution are determined from events in the 1.75–1.85-GeV mass region and are subtracted from the data. For the multiplicity analysis, K_S^0's are not identified, and so charged pions from their decay are included in the number of charged particles. The produced multiplicity distributions are unfolded from the observed multiplicity distributions by a Monte Carlo technique simulating $D^0\bar{D}^0$ and D^+D^- production at the $\psi(3772)$. The unfold includes a correction to remove the contribution of e^+e^- pairs from photon conversions in the detector.

The observed and unfolded multiplicity distributions are displayed in Fig. 1. We observe that the D^0 decays primarily into two charged particles, while the D^+ decays roughly equally into states containing one and three charged particles. The average unfolded multiplicities for the D^0 and for the D^+ are found to be the same. They are

$$\langle n_c \rangle_{D^0} = 2.3 \pm 0.3,$$

$$\langle n_c \rangle_{D^+} = 2.3 \pm 0.3.$$

The D mesons are expected to decay predominantly into channels including one kaon. We measure the kaon content of D decays by counting the number of charged and neutral kaons in the recoil system of the tagged events. Charged kaons are

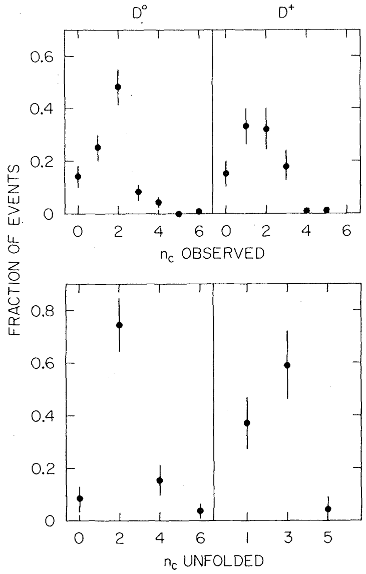

FIG. 1. Observed and produced (unfolded) charged multiplicity distributions for D^0 and D^+ decays. Errors are statistical only.

identified by their time of flight for a 1.5–2.0-m flight path in the magnetic detector. The time resolution is $\sigma_T = 0.4$ ns. For momenta below 450 MeV/c the separation between pions and kaons is unambiguous. For momenta greater than 450 MeV/c, the number of kaons is determined by fits to the time-of-flight spectrum in narrow momentum bins. For each momentum bin the spectrum is fitted to the sum of two Gaussians, kaons and pions. The means and widths of the two Gaussians are known. The only fitted parameters are the numbers of kaons and pions. In most cases (including all of the $D^\pm$ fits), the results thus obtained are virtually the same as would result from a simple momentum-dependent cut on the time of flight. The advantages of the fitting procedure are that it resolves those few cases where there are tracks in the overlap region between the kaon and pion Gaussians and it provides an estimate of the error arising from K-π ambiguity as well as the statistical error. We find that the statistical error is dominant.

Neutral kaons are identified by measurement of the di-pion mass and the consistency of the di-pion vertex position with the direction of the kaon momentum.[8]

The numbers of charged and neutral kaons found in the D^0 and $D^\pm$ recoil systems are shown in Table I. For the charged kaons in the $D^\pm$ events we make a distinction between "right-sign" and "wrong-sign" kaons. Right-sign kaons have the opposite charge from the kaon in the observed $D^\pm$. Wrong-sign kaons have the same charge as the kaon in the observed $D^\pm$. In the Glashow-Iliopoulos-Maiani (GIM) model,[9] decays containing wrong-sign kaons are suppressed by a factor of $\tan^2(\theta_C)$, where θ_C is the Cabibbo angle (~13°). Such a distinction has not been made for the charged kaons in the D^0 events because in the observed decay $D^0 \to K^\mp \pi^\pm$ the momentum of the kaon and the pion are too high to reliably distinguish them by time of flight on an event-by-event basis, so that there is an ambiguity between D^0 and $\bar{D}^0$.

Table I also shows the number of kaons in each category expected from background events (as determined from events in the 1.75–1.85-GeV mass region), and, for K^0's, from random two-pion combinations. After subtracting the background we correct for geometrical acceptance, losses due to two charged particles in the same time-of-flight counter, tracking efficiency, decays in flight of charged kaons, neutral decays of K_S^0, and unseen K_L^0's, to obtain the branching fractions shown in the last column of Table I.

A somewhat surprising result is the low branching fraction, 0.10 ± 0.07, for the decay of a charged D into a right-sign charged kaon. This implies that if the majority of charged-D decays contain a kaon, then decays into neutral kaons must dominate by a large factor.[10] Unfortunately,

TABLE I. Fractions of charged and neutral kaons in D^0 and D^+ decays.

Mode	No. of events found	No. of expected background events	Efficiency	Branching fraction
$D^0 \to K^\pm X$	21.2 ± 5.1	2.4 ± 0.6	0.46	0.35 ± 0.10
$D^0 \to K^0 X$	7 ± 2.6	1.1 ± 0.8	0.09	0.57 ± 0.26
$D^+ \to K^- X$	4.8 ± 2.2	1.4 ± 0.5	0.42	0.10 ± 0.07
$D^+ \to K^+ X$	2.8 ± 1.7	1.1 ± 0.4	0.39	0.06 ± 0.06
$D^+ \to K^0 X$	4 ± 2.0	1.3 ± 0.8	0.09	0.39 ± 0.29

TABLE II. Fractions of D^0 and D^+ energy going into pions, kaons, electrons and photons. The errors are statistical errors only.

	$\pi^{\pm}$	$K^{\pm}$	K^0	$e^{\pm}+\mu^{\pm}$	γ	Total (excluding ν's)
D^0	0.53 ± 0.06	0.15 ± 0.04	0.21 ± 0.11	0.03 ± 0.01	0.23 ± 0.10	1.15 ± 0.16
$D^{\pm}$	0.57 ± 0.08	0.06 ± 0.04	0.16 ± 0.14	0.03 ± 0.01	0.20 ± 0.12	1.02 ± 0.21

our low acceptance for neutral kaons and the small number of events do not permit a sufficiently accurate measurement to test this hypothesis.

An alternative method of studying the kaon content of D decays is to measure the inclusive kaon rate on and off the $\psi(3772)$ resonance.[11] By subtracting the latter from the former, we obtain the contribution of the resonance. We then determine the average number of kaons per D decay assuming that the only important decay mode of the $\psi(3772)$ is $D\bar{D}$. The advantage of this technique is that the number of kaons detected is large (~ 1000 K_S^0 and ~ 8000 $K^{\pm}$). The principal disadvantage is that the contributions of neutral and charged D's, and of right-sign and wrong-sign kaons, are not separated. The results of this analysis are that there are 0.52 ± 0.14 neutral kaons and 0.42 ± 0.12 charged kaons per D decay, where the errors are due primarily to systematic effects. On the assumption that the D^0:D^+ production ratio at the $\psi(3772)$ is 56:44,[1] these values should be compared to 0.49 ± 0.19 neutral kaons and 0.27 ± 0.07 charged kaons per D decay determined from the tagged events.

Another question that can be investigated by our inclusive studies is the average division of the available energy in D decays between kaons, charged pions, electrons, and muons, and photons (most of which presumably come from neutral-pion decays).

The energy carried by charged particles and by K_S^0's (as seen by the $\pi^+\pi^-$ decay mode) is determined by momentum measurement in the magnetic detector with a resolution $\sigma_p/p = 0.013p$ (p in GeV/c). Charged kaons are identified by time of flight, as described above. No attempt has been made to separate electrons and muons from pions in these tagged events. Instead, their contribution is computed from the average semielectronic branching ratio of the D mesons and the electron momentum spectrum, previously published.[3] The electron and muon contribution is then subtracted from the measured charged-pion contribution. We have assumed equality between semileptonic decays into electrons and muons as well as equality between D^0 and D^+ semileptonic branching ratios.

Photons are detected using an array of lead-glass counters added to one side of the magnetic detector and covering a solid angle of $0.053\times4\pi$ sr.[12] The photon energy resolution is $\sigma_E/E = 0.09/\sqrt{E}$ (E in GeV).

After background subtraction and efficiency corrections we obtain the fractions of energy carried by pions, kaons, electrons and muons, and photons shown in Table II. The energy carried by pairs of pions from K_S^0 decays has been explicitly subtracted from the charged-pion and photon fractions.

The measured fraction of energy carried by photons is approximately the same in the D^0 and $D^{\pm}$ decays and the average is equal to 0.22 ± 0.08. This average is consistent with being equal to half the total energy carried by charged pions, averaged over the D^0 and $D^{\pm}$ (0.28 ± 0.03). To the extent that these photons come from π^0's, the energy fraction of D-meson decays found in π^0's is thus consistent with half that found in charged pions.

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[5]With limited statistics, these "tagged" events can

also be used to measure exclusive decay branching ratios. The results are in agreement with those presented in Ref. 1.

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[10]Predominance of neutral over charged kaons from charged-*D* decay is expected, although not to the extent implied by this measurement. Since, in the GIM model, the charged *D* decays to a charged kaon of the opposite sign, its decay is inhibited by the necessity of producing two additional charged particles to conserve charge. One can try to estimate the expected magnitude of this inhibition by constructing a statistical model which reproduces our observed average multiplicity. Such a model predicts about 3 times as many neutral kaons as charged kaons in charged-*D* decays. See J. L. Rosner, in Institute for Advanced Study Report No. COO-2220-102, 1977 (unpublished), for a discussion of statistical models.

[11]Details of this measurement, along with measurements of *D* and *K* production at other center-of-mass energies, can be found in I. Peruzzi *et al.*, Lawrence Berkeley Laboratory Report No. LBL-7935, 1978 (to be published).

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Evidence for Energy Thermalization in Deep-Inelastic Processes: ^{63}Cu+^{20}Ne at 7.9, 12.6, and 17.2 MeV/Nucleon

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Light–charged-particle emission in the reaction ^{63}Cu + ^{20}Ne has been studied by simultaneously measuring the atomic numbers of both deep-inelastic fragments. The results seem consistent with an evaporative process and indicate that the entrance-channel kinetic energy is essentially thermalized over a broad range of bombarding energies.

On the basis of single-particle inclusive measurements,[1,2] it is evident that a large fraction of the entrance kinetic energy in heavy-ion reactions is dissipated in deep-inelastic collisions (DIC). However, the mechanism responsible for the damping process is not obvious, and a variety of mechanisms have been proposed (see, for example, Refs. 3–5). Correlation measurements between deep-inelastic fragments and either light particles[6-10] or heavy fragments[11-13] are powerful techniques for exploring the details of the dissipation process. Furthermore, such studies can also yield information on the relaxation of other modes like the degree of thermalization of the dissipated energy and the sharing of excitation energy between the primary fragments. There are, however, limitations associated with both techniques. Light-particle coincidence experiments are complicated by the fact that the spatial correlations can be broad and the interpretation tends to be difficult at high excitation energies when both fragments can emit one or more particles. In addition, the presence of small amounts of light target impurities can seriously contaminate the light-particle spectra. On the other hand, coincidence measurements of the heavy fragments necessitate very accurate energy and angular calibrations if meaningful results are to be extracted on the basis of deviations from two-body kinematics.

In this Letter we present results obtained with a technique which avoids the above difficulties, and, at the same time, provides a global view of light–charged-particle emission. The atomic numbers of both deep-inelastic fragments produced in the reaction ^{63}Cu + ^{20}Ne have been measured simultaneously, thus allowing the total charge loss (ΔZ) to be determined directly. This system was chosen because the singles measurements have been performed,[14] and because this technique is optimized for light systems. More importantly, ^{20}Ne beams were available at high energies where one might possibly expect nonstatistical particle emission to play a dominant role in the energy dissipation process.

A self-supporting, 560-μg/cm^2-thick ^{63}Cu foil (99% enrichment) was bombarded with ^{20}Ne ions accelerated by the Lawrence Berkeley Laboratory 88-in. cyclotron. The energies, atomic numbers, and laboratory angles of the two heavy fragments were measured with two large–solid-angle (5° angular acceptance) particle telescopes,

