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Study of D Mesons Produced in the Decay of the $\psi(3772)$

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From a study of D mesons produced in the decay $\psi(3772) \to D\bar{D}$, we have determined the masses of the D^0 and D^+ mesons to be 1863.3 ± 0.9 MeV/c^2 and 1868.3 ± 0.9 MeV/c^2, respectively. Under the assumption that the $\psi(3772)$ has a definite isospin and decays only to $D\bar{D}$, the D^0 branching fractions to $K^-\pi^+$, $\bar{K}^0\pi^+\pi^-$, and $K^-\pi^+\pi^-\pi^+$ are $(2.2 \pm 0.6)\%$, $(4.0 \pm 1.3)\%$, and $(3.2 \pm 1.1)\%$ and the D^+ branching fractions to $\bar{K}^0\pi^+$ and $K^-\pi^+\pi^+$ are $(1.5 \pm 0.6)\%$ and $(3.9 \pm 1.0)\%$.

The recently discovered[1] $\psi(3772)$ (ψ'') provides a rich source of kinematically well-defined and relatively background-free D mesons. In this Letter we use this source to determine the D masses with much more precision than has been previously possible. All of the D and D^* mass differences and transition Q values are now accurately known. Employing reasonable assumptions about the nature of the ψ'', we calculate for the first time absolute branching fractions for five D decay modes including the previously unreported mode $D^+ \to \bar{K}^0\pi^+$. We also show that the production angular distributions are consistent with the hypothesis that D mesons are spinless particles.

The data were collected with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at SPEAR.[2,3] The analysis techniques are similar to those described previously.[4,5] Based on time-of-flight measurements each particle in a multihadronic event is assigned a weight proportional to the probability that it is a π, K, or p. All possible combinations of tracks and particle hypotheses are weighted by the joint probability that the tracks satisfy the particular particle hypotheses assigned to them. Since all of the distributions discussed here contain a relatively small amount of background, each combination is plotted with unit weight if its weight exceeds a threshold.[6] For $K^\mp\pi^\pm$ combinations the threshold is 0.01, but for any two particles only the combination with higher weight is used. For other modes the threshold is 0.3 to eliminate ambiguities between modes such as $K^\mp\pi^\pm\pi^+\pi^-$ and $K_s^0\pi^+\pi^-$. Neutral kaons are identified by measurement of the dipion mass and the consistency of the dipion vertex position with the kaon line of flight.[7]

Figure 1 shows the product of the cross section and branching ratio (σB) for the $K^\mp\pi^\pm$ decay

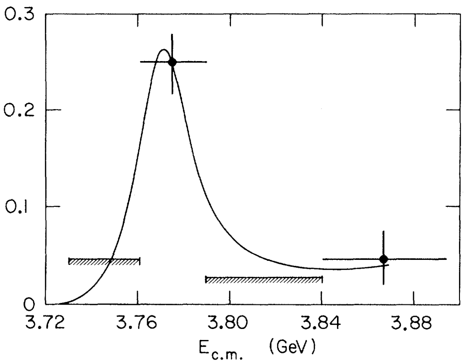

FIG. 1. σB for D^0 $(\bar{D}^0) \to K^{\mp}\pi^{\pm}$ as a function of $E_{c.m.}$. The cross-hatched bars represent 90%-confidence-level upper limits. The curve represents the fit to the ψ'' line shape and charmed-particle background from Ref. 1 normalized to the $E_{c.m.} = 3.774$ GeV point.

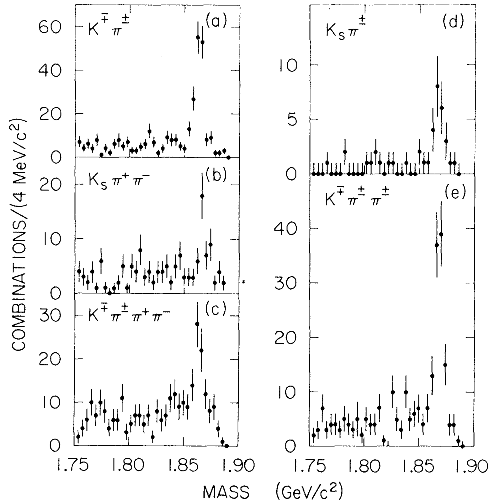

FIG. 2. Invariant-mass spectra for various D decay modes. See text for a discussion of cuts and techniques.

modes of the D^0 and $\bar{D}^0$ as a function of center-of-mass energy ($E_{c.m.}$) along with the parametrization of the ψ'' line shape and the charmed-particle background from Ref. 1. $D\bar{D}$, the only kinematically allowed channel involving D mesons, is clearly one of the decay modes of the ψ''. We restrict the remainder of the analysis to a sample of about 25 000 hadronic events corresponding to an integrated luminosity of 1.21 pb^{-1} near the peak of the ψ'', in the $E_{c.m.}$ range 3.76–3.79 GeV. About 70% of this data sample was collected at the fixed energy of 3.774 GeV.

A useful property of the reaction $e^+e^- \to D\bar{D}$ is that each D meson has the energy of one of the incident beams ($E_b = \frac{1}{2}E_{c.m.}$). We can thus calculate the mass of a particle combination which is a candidate for a D-meson decay from

$$m = (E_b^2 - p^2)^{1/2}. \quad (1)$$

Since E_b has a much smaller spread than the measured energy of a particle combination, and since the momentum, p, of the combination is small (~300 MeV/c), m is determined five to ten times more precisely from Eq. (1) than from a direct measurement.

For each particle combination we first require that the measured energy agree with E_b to within 50 MeV and then calculate the mass from Eq. (1). The results, given in Fig. 2, show clear signals in five modes including the previously unreported mode $D^{\pm} \to K_S^0\pi^{\pm}$. The observed rms width of about 3 MeV/c^2 are consistent with those expected from experimental resolution alone.

Table I gives the D masses determined from fits to the data in Fig. 2 plotted in finer bins. The errors are calculated by combining the statistical (0.3–0.4 MeV/c^2) and systematic (0.8 MeV/c^2) uncertainties in quadrature. Two important contributions to the systematic uncertainty are the absolute momentum calibration (0.5 MeV/c^2) and the long-term stability of E_b monitoring (0.5 MeV/c^2). The 0.13% uncertainty in the absolute SPEAR energy calibration is not included in the error. Technically, what is being measured is the ratio of the D mass to the ψ mass where the ψ mass is taken to be 3095 MeV/c^2.

TABLE I. Masses, mass differences, and Q values for the D-meson system. The quantities in parentheses are taken from Refs. 5 and 8 and are used in the calculation of quantities involving D^*'s. All units are MeV/c^2. See text for a discussion of errors.

Mass (MeV/c^2)		Mass difference (MeV/c^2)		Q values (MeV/c^2)	
D^0	1863.3 ± 0.9	$D^+ - D^0$	5.0 ± 0.8	$D^{*0} \to D^0\pi^0$	7.7 ± 1.7
D^+	1868.3 ± 0.9	$D^{*+} - D^{*0}$	2.6 ± 1.8	$D^{*0} \to D^+\pi^-$	−1.9 ± 1.7
D^{*0}	(2006 ± 1.5)	$(D^+ - D^0) - (D^{*+} - D^{*0})$	2.4 ± 2.4	$D^{*+} \to D^0\pi^+$	(5.7 ± 0.5)
D^{*+}	2008.6 ± 1.0			$D^{*+} \to D^+\pi^0$	5.3 ± 0.9

TABLE II. Number of combinations, efficiency, cross section times branching fractions (σB), and branching fractions for various D decay modes. The absolute-branching-fraction determination depends on assumptions discussed in the text.

Mode	Number of combinations	Efficiency	σB (nb)	B (%)
$K^{\mp}\pi^{\pm}$	130 ± 13	0.42	0.25 ± 0.05	2.2 ± 0.6
$K^0\pi^+\pi^-$ + c.c.	28 ± 7	0.05	0.46 ± 0.12	4.0 ± 1.3
$K^{\mp}\pi^{\pm}\pi^+\pi^-$	44 ± 10	0.10	0.36 ± 0.1	3.2 ± 1.1
$\bar{K}^0\pi^+$ + c.c.	17 ± 5	0.10	0.14 ± 0.05	1.5 ± 0.6
$K^{\mp}\pi^{\pm}\pi^{\pm}$	85 ± 11	0.19	0.36 ± 0.06	3.9 ± 1.0

With the addition of the previous measurements of the D^{*0} mass[8] and the Q value for $D^{*+} \to D^0\pi^+$,[5] all of the D and D^* masses are known with uncertainties of 1.5 MeV/c^2 or less. The mass differences and Q values for D^* pionic decays are given in Table I to include explicitly the calculation of correlated errors. For example, the D^+-D^0 mass difference, 5.0 ± 0.8 MeV/c^2, is known more precisely than either D mass because several systematic errors cancel in the mass difference.

Table II gives the values of σB for each of the five decay modes shown in Fig. 2. The techniques used in calculating the detection efficiencies shown in Table II are the same as those used by Piccolo *et al.*[9,10]

To obtain absolute branching fractions we need two quite reasonable assumptions: (1) that the ψ'' is a state of definite isospin, either 0 or 1, and (2) that its only substantial decay mode is $D\bar{D}$. The rationale for the latter assumption is that the ψ' and ψ'' differ in mass by only 88 MeV/c^2 and thus should have similar decay modes to channels which are open to both states. However, the total ψ'' width is two orders of magnitude larger than the ψ' width. The simplest explanation for the difference in widths is to attribute most of the ψ'' width to the $D\bar{D}$ channel, which is accessible to it, but not to the ψ'. The first assumption gives equal ψ'' partial widths to $D^0\bar{D}^0$ and D^+D^- except for factors which depend on the D momentum. In Ref. 1, the partial widths were assumed to be proportional to $p^3/[1+(rp)^2]$ where p is the D momentum and r is an interaction radius. As r is varied from 0 to infinity, the fraction of $D^0\bar{D}^0$ changes from 0.59 to 0.53. We thus take this fraction to be 0.56 ± 0.03. The error due to the uncertainty in r is small compared to other systematic errors. Given these assumptions and the data from Ref. 1, the D^0 ($\bar{D}^0$) and $D^{\pm}$ inclusive cross sections for this data sample are 11.5 ± 2.5 nb and 9.1 ± 2.0 nb, respectively.[11,12] The absolute branching fractions derived under these assumptions are given in Table II.

In Table II we have accounted for $(9.4 \pm 2.3)\%$ of D^0 decays and $(5.4 \pm 1.3)\%$ of D^+ decays. The unidentified decays are not detected by the techniques discussed here either because they contain neutral particles, have too small a branching fraction, have too small a detection efficiency, or are obscured by backgrounds.

The angular distribution of D's relative to the

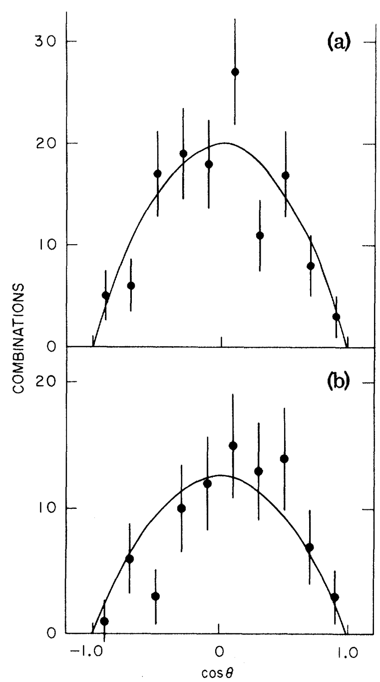

FIG. 3. Cosine of the angle between the incident e^+ beam and the D momentum for (a) D^0 ($\bar{D}^0$) $\to K^{\mp}\pi^{\pm}$ and (b) $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$, after background subtraction. The curves represent $\sin^2\theta$, the required distribution for the production of spinless D mesons.

incident beams must be of the form

$$P(\theta) \propto 1 + \alpha \cos^2, \quad |\alpha| \leq 1, \tag{2}$$

for any D spin and α must be -1 for spin 0. Figure 3 shows the angular distribution for the $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ decays. The values of α are found to be -1.04 ± 0.10 and -1.00 ± 0.09, respectively, consistent with the assignment of spin 0 for the D mesons.[13]

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[6] See Ref. 5 for the rationale for this procedure and an example of how it works in practice.

[7] V. Lüth *et al.*, Phys. Lett. 70B, 120 (1977).

[8] G. Goldhaber *et al.*, Phys. Lett. 69B, 503 (1977).

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[10] The efficiency for the $K^\mp\pi^\pm$ mode is substantially larger here than in Ref. 9 because less restrictive time-of-flight requirements were needed and because the K and π are more collinear, which results in a larger geometrical acceptance. The ratios of σB values for the three D^0 decay modes are in good agreement with those which can be derived from Ref. 9.

[11] A revised calculation of the external radiative corrections for e^+e^- collinear events has resulted in a 7.5% increase of the evaluated luminosity and in a consequent decrease of the cross sections reported in Refs. 1, 3–9 (A. M. Boyarski, private communication). The revised ψ'' partial width to electron pairs is 345 ± 85 eV.

[12] A possible contribution to the total cross section due to τ production (which could be as large as 7%) has not been explicitly subtracted.

[13] See H. K. Nguyen *et al.*, Phys. Rev. Lett. 39, 262 (1977) for additional experimental evidence on D and D^* spins.

Decays of Heavy Vector Mesons into Higgs Particles

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Estimates are presented for the decay of vector mesons composed of heavy quarks into states containing a Higgs boson. If the decays are kinematically allowed, they are probably experimentally accessible when the quark mass $m_q \gtrsim 4$ GeV.

Present-day gauge theories of the weak interactions require the existence of scalar particles (Higgs mesons) with characteristic properties. Discovery of such particles would be weighty evidence in favor of such theories. Because these mesons are thought to be very weakly coupled, all processes hitherto considered for production and detection gave poor prospects for experimental success.[1] In this Letter I would like to point out that this situation can be much improved if e^+e^- colliding-beam machines produce particles analogous to the J/ψ but with larger mass.[2]

Let us briefly recall the relevant properties of Higgs mesons. For definiteness I shall discuss the original model of Weinberg and Salam[3] with new quarks and leptons added sequentially. In this model the coupling of the Higgs meson H to a quark q or lepton l of mass m is given by

$$\mathcal{L}_{\text{int}} = 2^{1/4} G_F^{1/2} m H(q\bar{q} \text{ or } l\bar{l}). \tag{1}$$

The close connection between the Higgs coupling strength and the fermion mass is characteristic. It immediately suggests that the use of particles containing heavy quarks in the search for Higgs particles will be profitable. For instance, if the mass m of the quark is 7.6 GeV, then the Higgs coupling already has $\frac{1}{10}$ the strength of the electromagnetic coupling. (Actually, if we remember that quarks are fractionally charged, the ratio is even larger.) The mass of the Higgs particle itself is unfortunately not predicted in the model.

It is easy to compute the ratio of the processes $V \to \mu\mu$, $V \to H\gamma$ (where V is a vector meson formed from quarks of mass m_q), assuming that