Measurement of Semileptonic Decays of D Mesons to Electrons at the $\psi(3772)$

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We have observed anomalous electron production in multiprong events produced by e^+e^- annihilation at the $\psi(3772)$. For electron momenta greater than 300 MeV/c we measure an anomalous electron production cross section of 1.1 ± 0.3 nb. The measured spectrum is consistent with that expected for semileptonic D decay. With reasonable assumptions we find the branching ratio for D decay to an electron plus additional particles, averaged over the neutral and charged D, to be $(7.2 \pm 2.8)\%$.

The $\psi(3772)$,[1] through its decay into $D\bar{D}$, is a source of charmed D mesons with well-defined kinematics. In a previous paper[2] we used the $\psi(3772)$, produced in e^+e^- collisions, to determine D-meson mass values and absolute branching ratios into hadronic decay channels. In this Letter we report on a measurement of anomalous electron production in events with three or more detected charged particles (multiprong events) at the $\psi(3772)$. With these data we can study the semileptonic decay of the D meson in a reaction in which the D production mechanism is known and in which the center-of-mass energy ($E_{\text{c.m.}}$) is below the threshold for the production of any other type of charmed particle.[3] We find production of anomalous electrons with a momentum spectrum that is consistent with that expected for semileptonic D decay, and calculate, under reasonable assumptions, the branching ratio for the decay of the D into an electron plus additional particles.

This experiment was performed at SPEAR with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-LBL) magnetic detector.[4] Two layers of lead-glass counters for improved identification of electrons were added to the detector. The lead-glass system (called the LGW) has been described elsewhere.[5] The first layer consists of a set of active converters that are 3.3 radiation lengths ($3.3X_0$) deep. The second layer is made up of a set of back block counters that are $10.5X_0$ thick. The LGW covers a solid angle of 0.69 sr and is preceded by the $1X_0$ aluminum magnet coil of the magnetic detector.

The LGW has been used to measure anomalous electron production in e^+e^- collisions at the $\psi(3772)$. For our data sample we require that (1) a charged particle with momentum greater than 300 MeV/c enters the LGW (for clean electron identification), and (2) two or more additional charged particles are observed in the magnetic detector. For this analysis we use only the multiprong events in order to reduce contamination from quantum electrodynamic and possibly heavy-lepton events which are expected to appear mainly in the two-prong data sample.

The identification of particles that enter the LGW is based on the energy deposited in each of the two layers of lead-glass counters and on the measured time of flight. The energy deposition criteria for identifying a particle as an electron candidate are as follows: (i) The total energy deposited in the LGW equals the particle momentum as measured in the magnetic detector to within, typically, 35% (the exact value is momentum dependent), (ii) the energy deposited in the active converters exceeds a momentum-dependent threshold (typically 150 MeV) that is substantially greater than the 80 MeV expected for a noninteracting particle, and (iii) more than 10% of the energy of the particle is deposited in the back block counters. In addition, to reduce background from misidentification of kaons, protons, and antiprotons, we require that the measured time of flight of the particle agrees to within 1 nsec with that expected for an electron.

Electron candidates in the LGW may arise from (a) hadrons which interact in the magnet coil or active converters so as to satisfy the above criteria, (b) conventional sources of electrons such as pion and kaon decay, photon conversion, Compton scattering, and Dalitz decay of π^0's and η's, and (c) nonconventional (anomalous) sources of electrons such as decays of charmed particles and heavy leptons. Sources (a) and (b) produce a background to the anomalous electron signal from source (c).

The background from photon conversion and Dalitz decay is reduced by eliminating electron candidates that have a small opening angle with a particle of opposite charge. Background from asymmetric e^+e^- pairs in which one member of a pair is unobserved because its momentum is below the threshold for efficient detection (about 100 MeV/c) will still be present. To determine this background, as well as the background due to hadron misidentification and pion and kaon decays, we assume that there is no anomalous electron production at the $\psi(3095)$ and measure the background level there. In multihadronic events from $\psi(3095)$ decay we find that 1.5% of the particles in the LGW are identified as electrons at a momentum of 300 MeV/c. This fraction decreases with momentum to 0.4% at 1200 MeV/c. The background level at the $\psi(3772)$, expressed as a fraction of the particles in the LGW, should be similar. However, we must take account of changes in, and additions to, the conventional sources of electrons.

The background level at the $\psi(3772)$ from converted photons and Dalitz decays might differ from that at the $\psi(3095)$ because of a change in the flux of photons and π^0's above 300 MeV. The difference in this background level was determined by measuring, at the two energies, conversion e^+e^- pairs with both particles detected, then extrapolating to the case with one particle undetected. We find this background level at the $\psi(3095)$ and $\psi(3772)$ to be the same to within 10% of the measured background level at the $\psi(3095)$. Changes in the background level due to pion and kaon decays and Compton scattering were calculated to be less than 5% of the measured background.

Two additional sources of background events at the $\psi(3772)$ must be considered: (a) $e^+e^- \to e^+e^-\gamma$ with the photon converting to an e^+e^- pair, and (b) production of $\psi(3684)$, by radiation from the initial e^+ or e^-, followed by the cascade decay to $\psi(3095)$ with $\psi(3095) \to e^+e^-$. These events are recognized on the basis of coplanarity, invariant mass, electron identification outside the LGW, and associated e^+e^- pair production, and have been removed from the data sample. In summary, we use the background level as measured at the $\psi(3095)$ and assign an error of $\pm 20\%$ to this background estimation for the $\psi(3772)$.

The electron identification efficiency ϵ has been measured using a sample of electrons from the reactions $e^+e^- \to e^+e^-\gamma$ and $e^+e^-e^+e^-$. The value of ϵ ranges from 60% at a momentum of 300 MeV/c up to 90% at a momentum of 1200 MeV/c.

In the $E_{\rm c.m.}$ range about the peak of the $\psi(3772)$, $3.76 < E_{\rm c.m.} < 3.79$ GeV, with a time-integrated luminosity of 1.34 pb^{-1}, we find 61 multiprong events with a particle identified as an electron candidate in the LGW. The expected number of background events due to hadron misidentification and electrons from conventional sources is 25 ± 5. We attribute the electron signal above background to a nonconventional source. Correcting the number of electron candidate events for background, solid angle, and identification efficiency of the lead-glass wall, and form detection efficiency for the other prongs, we calculate the cross section for multiprong events with an anomalous electron of momentum greater than 300 MeV/c to be 1.1 ± 0.3 nb. This cross section, with data points from nearby energy regions, is plotted in Fig. 1 along with the excitation curve of the $\psi(3772)$ from Ref. 1. The anomalous electron signal appears to be correlated with the $\psi(3772)$. In Fig. 2 we show the corrected momentum distribution for the anomalous electrons produced at the $\psi(3772)$.

The $\psi(3772)$, in agreement with our previous observations, is expected to decay almost entirely into $D\bar{D}$.[2,6] This strongly suggests that the anomalous electron signal at the $\psi(3772)$ comes from the decay of the charmed D mesons. For comparison with the data, we also show in Fig. 2 the electron

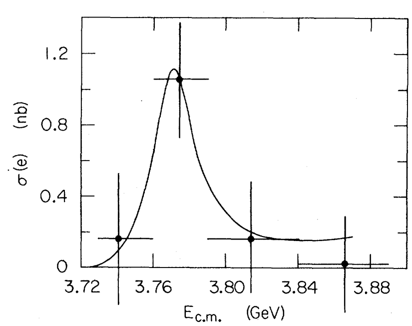

FIG. 1. The e^+e^- annihilation cross section for multiprong events with an anomalous electron of momentum greater than 300 MeV/c vs the center-of-mass energy. The curve is the $\psi(3772)$ line shape and charmed-particle background from Ref. 1 and it is normalized to the cross section at 3.774 GeV.

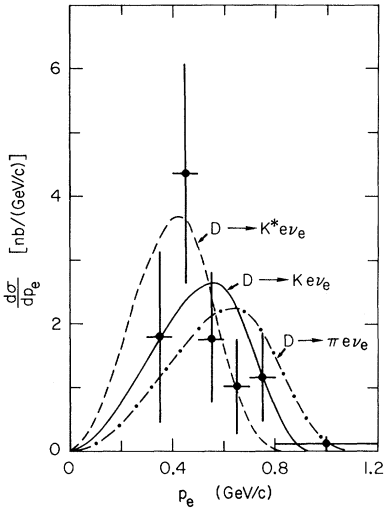

FIG. 2. The momentum spectrum above 300 MeV/c for the anomalous electrons produced in multiprong events at the ψ(3772). The curves show the electron spectra expected from D-meson production in the reaction $e^+e^- \to D\bar{D}$ followed by the decay $D \to Ke\nu_e$, $K^*e\nu_e$, or $\pi e\nu_e$, as noted in Ref. 7. The curves are normalized above 300 MeV/c to the measured cross section.

momentum spectra expected from D-meson production in $e^+e^- \to \psi(3772) \to D\bar{D}$ with subsequent semileptonic decay into $Ke\nu_e$, $K^*e\nu_e$, or $\pi e\nu_e$.[7] The data are consistent with the Cabibbo-favored decay modes $D \to Ke\nu_e$ [confidence level (C.L.) 33%] or $K^*e\nu_e$(C.L. 13%), but less consistent with electron production entirely from the Cabibbo-suppressed mode $D \to \pi e\nu_e$(C.L. 3%). The data are inconsistent with the purely leptonic decay $D \to e\nu_e$ which would produce a flat electron spectrum from about 810 to 1080 MeV/c.

Assuming that (a) the anomalous electron signal at the ψ(3772) comes entirely from D-meson production and decay,[8] and (b) that the ψ(3772) decays entirely into $D\bar{D}$, we can calculate the branching ratio $B_{D\to e}$ for D-meson decay into an electron plus other particles, averaged over the neutral and charged D.[9] We write $B_{D\to e} = \sigma(e)/\sigma(D)$, where $\sigma(e)$ is the anomalous electron-production cross section and $\sigma(D)$ is the cross section for D production. Under assumption (b) we have previously determined that $\sigma(D) = 20.6 \pm 4.3$ nb.[2] To evaluate $\sigma(e)$ we need to correct our measured anomalous electron cross section for (1) the part of the electron spectrum which falls below our cutoff value of 300 MeV/c, and (2) the fraction of $D\bar{D}$ events which produce an electron and only a single additional charged particle. For an estimate of the correction factor required by (1) we use the electron decay spectrum for $D \to Ke\nu_e$ or $K^*e\nu_e$ as shown in Fig. 2. The correction factor required by (2) is calculated from the measured charged-prong multiplicity distribution for D decay,[6] and the multiplicity distribution for $D \to Ke\nu_e$ or $K^*e\nu_e$. We find that $B_{D\to e} = (7.1 \pm 2.7)\%$ or $(7.3 \pm 2.8)\%$ with the correction factors evaluated from the spectrum and charged-prong multiplicity distribution for $D \to Ke\nu_e$ or $K^*e\nu_e$.[8] If another mode such as $K\pi e\nu_e$ (consistent with the measured spectrum) were dominant, the branching fraction obtained could differ, but we estimate the systematic error from this effect to be less than one-half the quoted errors.

In conclusion, we have observed anomalous electron production in multiprong final states produced by e^+e^- annihilation at the ψ(3772). The electron momentum spectrum is consistent with the Cabibbo-favored semileptonic decays of the D meson. We find, under the stated assumptions, and with correction factors for efficiency based on $D \to Ke\nu_e$ or $K^*e\nu_e$, a value for the branching ratio for D decay into an electron plus additional particles to be $(7.2 \pm 2.8)\%$.

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[1] P. A. Rapidis *et al.*, Phys. Rev. Lett. 39, 526 (1977).

[2] I. Peruzzi *et al.*, Phys. Rev. Lett. 39, 1301 (1977).

[3] Measurements at DORIS of anomalous electron production in multiprong events, at energies above the ψ (3772), can be found in W. Braunschweig *et al.*, Phys. Lett. 63B, 471 (1976); J. Burmester *et al.*, Phys. Lett. 64B, 369 (1976); R. Brandelik *et al.*, DESY Report No. 77/41, 1977 (to be published).

[4] J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[5] A. Barbaro-Galtieri *et al.*, 39, 1058 (1977).

[6] G. J. Feldman, SLAC Report No. SLAC-PUB-2000, 1977, in Proceedings of the 1977 Summer Institute on Particle Physics (SLAC, 1977, to be published).

[7] The electron momentum spectra are based on the calculations of A. Ali and T. C. Yang, Phys. Lett. 65B, 275 (1976), and A.Ali, private communication. We have used the $V-A$ form for the current which couples D to K^*

[8] If the ψ(3772) is above the threshold for $\tau^+\tau^-$ produc-

tion, an anomalous electron signal may also arise from decays of the heavy lepton τ. From preliminary measurements on $e\mu$ events at the $\psi(3772)$ [see M. L. Perl, in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977 (to be published)], we estimate that 6% of the anomalous electron events can come from this source. Taking account of $\tau^+\tau^-$ production would also lead to a decrease in the value of $\sigma(D)$ by about 12%; the net effect is to raise our value for the branching ratio of D to electrons from 7.2% to 7.6%.

[9]With the assumption that the $\psi(3772)$ is a state of definite isospin (0 or 1), this average corresponds to $(0.56 \pm 0.03)B_{D^0\to e} + (0.44 \pm 0.03)B_{D^+\to e}$, as noted in Ref. 2.

Meron Pairs and Quark Confinement

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We discuss the consequences of our classical meron-pair model on the quark-confinement phase transition in an SU(2) Yang-Mills quantum field theory.

A phase transition of merons has been proposed by Callan, Dashen, and Gross[1] as a mechanism for quark confinement. We study the Wilson loop integral

$$\oint \exp(i\oint_C A_\mu dx^\mu) d\mu = e^{-TE(L)}, \qquad (1)$$

where $d\mu = Z^{-1}\exp(-\frac{1}{4}\int F\cdot F\,dx)[\mathfrak{D}A]$ and C is an $L\times T$ rectangular path. We propose a picture which yields a confining potential

$$E(L) \sim L^\epsilon, \quad 0 \leq \epsilon = \epsilon(L) \leq 1. \qquad (2)$$

Our value of ϵ depends on the density $\nu(a)$ of meron pairs with separation a, and is limited by $\epsilon \leq 1$ in our analysis.

In a previous paper[2] we obtained multiple meron configurations for classical SU(2) gauge fields. In studying (1) and (2) it is fundamental to minimize action plus entropy. Entropy of the classical meron configuration is associated with the location of each meron in R^4 and also with the assignment of bags to join the merons pairwise (cf. Ref. 2). Because we minimize action plus entropy, we do not insist that the configurations allowed are solutions of the classical Yang-Mills equations (derived by minimization of the action alone) (cf. Ref. 1 and Mueller[3]). In particular we analyze configurations formed from meron pairs whose bags may overlap.

Since the action for a meron pair is logarithmic in the separation a, and since the effective coupling constant $\bar{g}(a)$ for distance a is a slowly increasing function of a by a renormalization-group argument, we postulate a density

$$\nu(a)\,da = a^{-4+\epsilon}\,da \qquad (3)$$

for meron pairs with separation a. Here $\epsilon = \epsilon(a)$ is a slowly increasing function of a, and (3) results from neglecting the interaction of distinct meron pairs. Note that $\epsilon < 0$ corresponds to nonoverlapping pairs while $\epsilon = 3$ corresponds to complete meron unbinding.

We have two main results. The first is similar to Ref. 1 and shows that (3) leads to a quark-confinement potential (2) if $\epsilon > 0$. The second is that at $\epsilon = 1$ (if not sooner for some $\epsilon < 1$) a phase transition to the strong-coupling regime occurs, in which the meron picture no longer applies. In this regime a linear confinement potential is known.[4]

In order to evaluate (1), we regard $A = \sum A_j$ as a sum of potentials A_j, each due to a single meron pair at random points and orientations, and subject to the constraint (3). Then

$$\langle \exp(i\oint A)\rangle \sim \exp[-\langle \tfrac{1}{2}(\oint A)^2\rangle] \sim \exp[-\tfrac{1}{2}\textstyle\sum\langle(\oint A_j)^2\rangle],$$

and so

$$E(L) \sim \sum_{t=0} \langle (\oint A_j)^2\rangle. \qquad (4)$$

Here $\sum_{(t=0)}$ restricts the sum over meron pairs to those pairs centered on the $t=0$ hyperplane, and we have taken T to infinity with fixed L, and center the loop at the origin.

Let r be the distance from the midpoint of the meron pairs to the time axis. A calculation using $\vec{A}$ as given in Ref. 2, below Eq. (25), shows that for meron-pair solution

$$|\oint A_j| = O(1)\left(\frac{a^2}{a^2+r^2}\right)\left(\frac{L}{L+r}\right), \qquad (5)$$

up to a factor of $\ln L$, which we ignore. Then sub-

