Observation of $e^+e^- \rightarrow D_s^\pm D_s^{*\mp}$ at $\sqrt{s}=4.14$ GeV

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We present evidence for the exclusive reaction $e^+e^- \rightarrow D_s^\pm D_s^{*\mp}$, observed with the Mark III detector at the SLAC storage ring SPEAR. The $D_s^\pm$ is reconstructed in the $\phi\pi^\pm$ decay mode, while the $D_s^{*\mp}$ is detected as a narrow peak in the recoil-mass distribution. The mass of the D_s^* is found to be $2109.3 \pm 2.1 \pm 3.1$ MeV/c^2, yielding a D_s^*-D_s mass difference of $137.9 \pm 2.1 \pm 4.3$ MeV/c^2. The width of the D_s^* is <22 MeV/c^2 at the 90%-confidence level. The observed signal corresponds to $\sigma(e^+e^- \rightarrow D_s^+D_s^{*-}+D_s^-D_s^{*+})\, B(D_s^+ \rightarrow \phi\pi^+) = 30 \pm 6 \pm 11$ pb at $\sqrt{s}=4.14$ GeV.

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In the quark model, the lowest-lying $c\bar{s}$ pseudoscalar meson, the D_s^+, has a higher-mass vector-meson partner, the D_s^{*+}.[1] In models with hyperfine corrections,[2] the D_s^{*+} mass is predicted to lie 80 to 150 MeV/c^2 above that of the D_s^+. Evidence has been presented for a narrow state decaying into a D_s^+ meson and a photon.[3,4] Exclusive production of this state in association with the D_s in e^+e^- annihilation would provide new evidence that it is indeed the D_s^*. This Letter reports the first evidence of the exclusive reaction $e^+e^- \rightarrow D_s^+D_s^{*-}$, where the $D_s^\pm$ is observed in the decay

$$D_s^+ \rightarrow \phi\pi^+ \tag{1}$$

or in the cascade

$$D_s^{*-} \rightarrow \gamma D_s^-, \quad D_s^- \rightarrow \phi\pi^-. \tag{2}$$

A precise measurement of the D_s^* mass is also reported.

The data sample represents an integrated luminosity of 6.30 ± 0.46 pb^{-1} at $\sqrt{s}=4.14$ GeV, collected with the Mark III detector at the SLAC storage ring SPEAR. A detailed description of the detector has been given elsewhere.[5] Tracking information from the drift chamber, and time-of-flight (TOF) measurements from scintillation counters, are used in this analysis.

The analysis proceeds with the isolation of events containing one or more ϕ's. A charged particle is identified as a kaon with use of TOF.[6] The π-K separation is better than 5σ for kaons from reactions (1) and (2).[7] Figure 1 shows the mass distribution of oppositely charged kaon pairs. The mass of a ϕ candidate is required to be within 10 MeV/c^2 of the nominal ϕ mass. The $\phi\pi$ candidates are selected by the combining of a ϕ with each of the remaining charged tracks, assumed to be pions. A scatter plot of the $\phi\pi^+$ mass versus the recoil mass is shown in Fig. 2. Evidence for $D_s^+D_s^{*-}$ production appears as a cluster of events near $M(\phi\pi^+)=1.97$ GeV/c^2 and $M(\text{recoil})=2.10$ GeV/c^2. Another cluster near $M(\phi\pi^+)=1.87$ GeV/c^2 and $M(\text{recoil})=2.01$ GeV/c^2 is evidence for production of D^+D^{*-}, with $D^+ \rightarrow \phi\pi^+$.[8] Figure 3(a) shows the

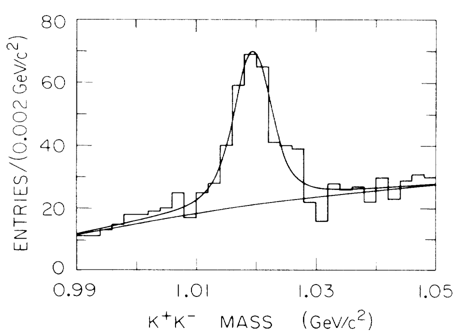

FIG. 1. The K^+K^- invariant-mass distribution. A fit to this distribution, with use of a Breit-Wigner line shape and a polynomial background, with $\Gamma(\phi)=4.2$ MeV/c^2, yields $M(\phi) = 1019.3 \pm 0.4$ MeV/c^2, and $\sigma = 2.1 \pm 0.8$ MeV/c^2.

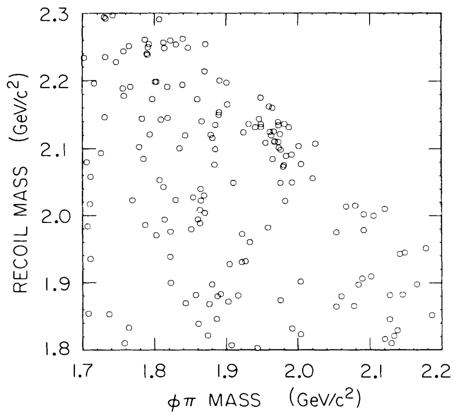

FIG. 2. Scatter plot of $M(\phi\pi^+)$ vs M(recoil).

recoil-mass distribution when the $\phi\pi^+$ mass is restricted to the D_s^+ region, 1.92 to 2.02 GeV/c^2. This distribution contains the recoil from the D_s^+'s produced in reactions (1) and (2). No significant evidence for $e^+e^- \to D_s^+D_s^-$, $D_s^+ \to \phi\pi^+$ is observed. The photon from the decay $D_s^{*+} \to \gamma D_s^+$ is not used in this analysis because of the limited energy resolution of the calorimeter. The D_s^* mass resolution would not be significantly improved, and the photon selection is ambiguous in events with many neutral showers.

The decay $D_s^+ \to \phi\pi^+$ is isolated by the requirement that the recoil mass lie between 2.04 and 2.18 GeV/c^2 [Fig. 3(b)]. An unbinned maximum-likelihood fit to this distribution with a Gaussian plus background yields 26.7 ± 5.2 (stat.) signal events above 5.6 background events. The fitted D_s^+ mass is $1972.4 \pm 3.7 \pm 3.7$ MeV/c^2. The background shape is determined from the $\phi\pi^+$ mass distribution obtained by the combination of ϕ candidates with pions from different events. The mass resolution determined by Monte Carlo simulation ($\sigma = 15.1$ MeV/c^2) is imposed in the fit. The systematic error includes variation of the selection criteria (2.4 MeV/c^2), and uncertainties in the background shape (2.5 MeV/c^2) and in the momentum scale[9] (1.1 MeV/c^2).

The analysis procedure and the absolute-mass scale are checked by investigating D decays in the data sample. The decay $D^+ \to \phi\pi^+$ is observed by the restricting of the recoil mass to the D^* mass region, 1.97 to 2.05 GeV/c^2. The result is shown in Fig. 3(c): A fit with a Gaussian and a flat background yields a D^+ mass of $1860 \pm 7 \pm 4$ MeV/c^2. The reactions $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and $D^+ \to K^-\pi^+\pi^+$ are analyzed with similar particle identification and recoil requirements, giving fitted masses of 1865.3 ± 1.2 MeV/c^2, 1865.3 ± 1.3 MeV/c^2, and 1870.6 ± 2.6 MeV/c^2, respectively (statistical errors only).

To improve the D_s^* mass resolution, a D_s mass[10] of 1971.4 MeV/c^2 is imposed as a constraint in the calculation of the recoil mass.[11] The resulting recoil-mass distribution (Fig. 4) shows a narrow peak at 2.11 GeV/c^2 from reaction (1), on a broad structure between 2.07 and 2.15 GeV/c^2 from reaction (2). A fit to this distribution yields

$$M(D_s^*) = 2109.3 \pm 2.1 \pm 3.1 \text{ MeV}/c^2.$$

The shape of the signal distribution and the resolution (5.0 MeV/c^2) are determined from a Monte Carlo simulation which includes radiative corrections.[12] The background shape is determined from K^+K^- sidebands around the ϕ. The systematic error includes contributions from the uncertainties in the D_s^+ mass (1.7 MeV/c^2), the center-of-mass energy at SPEAR (1.7

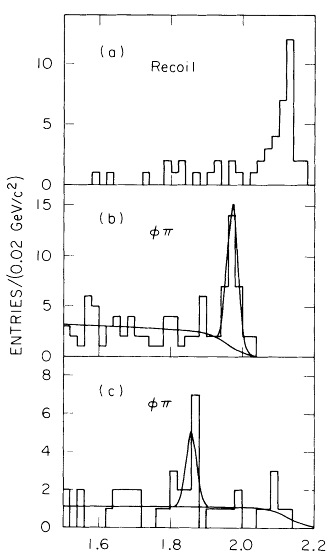

FIG. 3. (a) The projection of M(recoil) for $1.92 < M(\phi\pi^+) < 2.02$ GeV/c^2. (b) The projection of $M(\phi\pi^+)$ for $2.04 < M(\text{recoil}) < 2.18$ GeV/c^2. The fit is described in the text. (c) The projection of $M(\phi\pi^+)$ for $1.97 < M(\text{recoil}) < 2.05$ GeV/c^2.

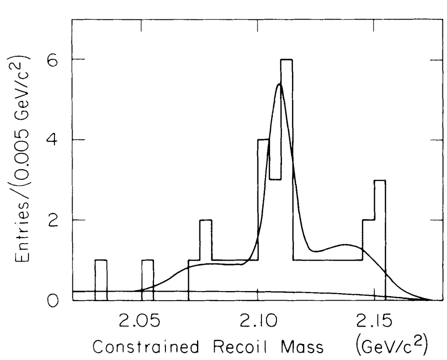

FIG. 4. The recoil-mass distribution with the D_s^+ mass constrained at 1971.4 MeV/c^2. The fit is described in the text.

MeV), the radiative corrections (1.2 MeV/c^2), the selection criteria (1.5 MeV/c^2), the background shape (0.5 MeV/c^2), and the momentum scale (0.1 MeV/c^2). The result implies[13]

$$M(D_s^*) - M(D_s) = 137.9 \pm 2.1 \pm 4.3 \text{ MeV}/c^2.$$

A maximum-likelihood calculation using the constrained recoil mass yields $\Gamma(D_s^*) < 22$ MeV/c^2 at 90%-confidence level. The width and mass of the D_s^* are allowed to vary, while the resolution is fixed.

The decay angle distributions for the ϕ in the D_s^+ helicity frame, and the K^+ in the decay ϕ helicity frame are shown in Fig. 5. Since the D_s^+ helicity frame cannot be determined for the D_s^+ decays produced in reaction (2), all events are assumed to arise from reaction (1). For the hypothesis $J^P(D_s) = 0^-$ and $J^P(D_s^*) = 1^-$, the confidence levels of the $\cos\theta_\phi$ and $\cos\theta_{K^+}$ distributions with use of the Kolmogorov-Smirnov test[14] are 0.62 and 0.39, respectively.

The production cross section times branching fraction is determined with the assumption of $B(D_s^{*+} \to \gamma D_s^+) = 100\%$. With use of the number of observed $D_s^+ \to \phi\pi^+$ decays (26.7 ± 5.2), and a $D_s^+ \to \phi\pi^+$ detection efficiency of 0.071, the result is

$$\sigma(e^+e^- \to D_s^+ D_s^{*-} + D_s^- D_s^{*+}) B(D_s^+ \to \phi\pi^+) = 30 \pm 6 \pm 11 \text{ pb}.$$

The systematic error includes contributions from the uncertainties in the detection efficiency (31%), the integrated luminosity (7%), and the background shape (15%). The contamination of the $\phi\pi^+$ sample by nonresonant $D_s^+ \to K^+K^-\pi^+$ decays is negligible (< 0.5 events) for $B(D_s^+ \to K^+K^-\pi^+) \simeq B(D_s^+ \to \phi\pi^+)$. The decay $D_s^+ \to \bar{K}^{*0}K^+ \to K^+K^-\pi^+$ does not feed into the $\phi\pi^+$ sample because it is excluded by the ϕ requirement on the K^+K^- mass. This mode will be addressed in a future Mark III publication.

The measured D_s^*-D_s mass difference can be compared with other vector-pseudoscalar splittings. For mesons containing at least one light quark, the mass-squared difference, $\Delta_{M^2} = M^2(1^-) - M^2(0^-)$, is approximately constant.[15] This effect has motivated calculations of the mass-squared difference within models which assume a simple confining potential.[16] These models predict $\Delta_{M^2} \simeq 64\pi\alpha_s |\psi(0)|^2/9\mu$, where $\psi(0)$ is the wave function at the origin and μ is the reduced mass of the quarks. An approximately constant mass-squared difference follows for specific choices of α_s and the form of the potential.[16] Our measurement of the D_s^*-D_s mass difference results in $\Delta_{M^2} = 0.563 \pm 0.020$ (GeV/c^2)^2, which is consistent with this empirical rule.

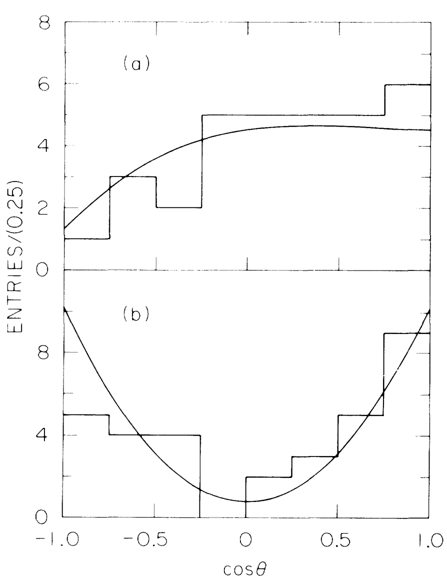

FIG. 5. (a) The $\cos\theta_\phi$ distribution in the D_s^+ helicity frame. (b) The $\cos\theta_{K^+}$ distribution in the ϕ helicity frame. The data are not acceptance corrected. The curves show the distributions from a Monte Carlo simulation which includes equal amounts of reactions (1) and (2), plus 18% background as determined from the fit to Fig. 3(b).

In summary, the exclusive reaction $e^+e^- \to D_s^+ D_s^{*-}$ at $\sqrt{s} = 4.14$ GeV is observed. The production cross section times branching fraction and the D_s^* mass are measured. The decay angular distributions are consistent with those expected for a pseudoscalar D_s and a vector D_s^*. These results are in good agreement with previous measurements of the D_s[17] and the D_s^*.[4]

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[1]The D_s^+ and D_s^{*+} were formerly denoted the F^+ and F^{*+}, respectively. Throughout this paper we adopt the convention that reference to a state also implies reference to its charge conjugate.

[2]For a recent discussion see S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985), and references therein.

[3]The first evidence for the D_s^{*+} was reported by R. Brandelik *et al.*, Phys. Lett. **70B**, 132 (1977), and R. Brandelik *et al.*, Phys. Lett. **80B**, 412 (1979). These measurements were not confirmed by R. Partridge *et al.*, Phys. Rev. Lett. **47**, 760

(1981), and R. P. Horisberger, Ph.D. thesis, SLAC Report No. 266, 1984 (unpublished).

[4]H. Aihara *et al.*, Phys. Rev. Lett. **53**, 2465 (1984); H. Albrecht *et al.*, Phys. Lett. **146B**, 111 (1984).

[5]D. Bernstein *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **226**, 301 (1984).

[6]The charged-kaon tracks are required to have $|(t_K^p - t^m)/\sigma_K| < |(t_\pi^p - t^m)/\sigma\pi|$, where t_K^p (t_π^p) is the predicted TOF for a kaon (π) mass hypothesis, t^m is the measured TOF, and σ_K (σ_π) is the TOF error for the kaon (π) mass hypothesis.

[7]In the Monte Carlo simulation, the D_s and D_s^* are assumed to be pseudoscalar and vector, respectively, with $B(D_s^* \to \gamma D_s) = 100\%$.

[8]The Cabibbo-suppressed decay $D^+ \to \phi\pi^+$ has been observed by R. Bailey *et al.*, Phys. Lett. **139B**, 320 (1984), and R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 150 (1985).

[9]The uncertainty in the absolute momentum scale, $\sigma(p)/p = 0.1\%$, has been estimated with use of the following reactions: $e^+e^- \to \mu^+\mu^-$; $K_S^0 \to \pi^+\pi^-$; $J/\psi \to p\bar{p}$; $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$; and $D^+ \to K^-\pi^+\pi^+$.

[10]A weighted average of $M(D_s^+) = 1971.4 \pm 1.7$ MeV/c^2 is obtained with use of the measurements tabulated in M. Aguilar-Benitez *et al.* (Particle Data Group), Phys. Lett. **170B**, 1 (1986), replacing the previous Amsterdam-Bristol-CERN-Cracow-Munich-Rutherford (ACCMOR) value with their later measurement, $M(D_s^+) = 1972.7 \pm 1.5 \pm 1.0$ MeV/c^2; H. Becker *et al.*, CERN Report No. CERN-EP/86-172, 1986 (to be published).

[11]$M(\text{recoil}) = (\{\sqrt{s} - [M^2(D_s) + p^2(D_s)]^{1/2}\}^2 - p^2(D_s))^{1/2}$, where $M(D_s)$ is fixed.

[12]Only initial state radiation is considered with use of a method from F. Behrends and R. Kleiss, Nucl. Phys. **B178**, 141 (1981).

[13]For $e^+e^- \to D_s^* D_s$ at $\sqrt{s} = 4.14$ GeV, $\delta M(D_s^*) \cong -\delta M(D_s)$. The systematic errors are $\sigma[M(D_s^*)] = \{(2.6\ \text{MeV}/c^2)^2 + \sigma^2[M(D_s)]\}^{1/2}$ and $\sigma[M(D_s^*) - M(D_s)] = \{(2.6\ \text{MeV}/c^2)^2 + 4\sigma^2[M(D_s)]\}^{1/2}$.

[14]D. B. Owen, *Handbook of Statistical Tables* (Addison-Wesley, Reading, MA, 1962).

[15]$\Delta_{M^2} = 0.575$ (GeV/c^2)^2 for $\rho^0 - \pi^0$, 0.556 (GeV/c^2)^2 for $K^{*0} - K^0$, and 0.551 (GeV/c^2)^2 for $D^{*0} - D^0$. For a discussion of the empirical relation see A. Martin, Comments Nucl. Part. Phys. **16**, 249 (1986).

[16]K. Igi and S. Ono, Phys. Rev. D **32**, 232 (1985); M. Frank and P. O'Donnell, CERN Report No. CERN-TH-4367/86, 1986 (to be published).

[17]M. Aguilar-Benitez *et al.*, in Ref. 10.