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[6] Luminosity event triggers of this type accounted for 4% of the total rate. After the experiment the association of these events with the backscattered γ rays from the S counters was directly and quantitatively verified in an electron test beam.

[7] The dimensions of the P counters were 2 in.×$1\frac{3}{8}$ in. ×$\frac{1}{8}$ in. and their heights and widths were measured to $\pm 10^{-3}$ in. Their vertical edges were tapered to be parallel to the incident particles and pulse heights smaller than the Landau edge were observed with a probability of ~ 0.1% for otherwise acceptable events.

[8] The length of the luminous region at SPEAR-II is small. By fitting to the observed distribution of vertex coordinates we find the luminous region to be 5.2 and 4.7 cm (full width at half-maximum) at center-of-mass energies of 7.4 and 7.0 GeV, respectively.

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Is Charm Found?*

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A new neutral narrow meson decaying into $K\pi$ and $K\pi\pi\pi$ was recently discovered in e^+e^- annihilation at SPEAR. Unexpected structure was observed in the recoil-mass spectrum associated with the new particle. We demonstrate that what has been seen coincides with what was expected by advocates of charm. We explain the observed suppression of $D\bar{D}$ production and the scarcity of charged D's. Predictions about the production of charmed hadrons not yet seen are given.

New hadrons are made copiously and in association by e^+e^- annihilation if ideas about charm are true.[1,2] Evidence for this has been reported.[3] We demonstrate that what has been seen conforms to theoretical expectations.

Weakly decaying pseudoscalar D mesons ($c\bar{u}$ and $c\bar{d}$) were predicted at 1.83 ± 0.03 GeV.[4] Their vector counterparts D^* are split from D by the color analog to electromagnetic spin-spin coupling. This mass splitting [or hyperfine splitting (hfs)] must be positive, like other "hyperfine splittings" (K^*-K, $\rho-\pi$, $\Delta-N$, etc.), but smaller because the charmed quark is heavy. We estimated[4] $M(D^*)-M(D) \sim M(\pi)$. Whether $D^* \rightarrow D\pi$ strongly or $D^* \rightarrow D\gamma$ electromagnetically depends on the precise hfs value.

Reported $K\pi$ and $K\pi\pi\pi$ enhancements at 1.865 ± 0.015 GeV are identified with D^0. No evidence for $D^\pm$ in $K\pi\pi$ is reported.[3] When D^0 is observed, the recoil mass is $\geqslant 1.86$ GeV as needs be if charmed mesons are produced in association. At e^+e^- energy $s^{1/2} \sim 4.1$ GeV, an enhancement in this recoil-mass distribution is seen at 2–2.2 GeV, possibly with unresolved structure. *What is the nature of the recoil spectrum and how will it change with energy? Why no recoil peak at 1.86 GeV? Where is* $D^\pm$?

Answers to these questions require analysis of quasi-two-body production of charmed mesons (including threshold, form factor, and spin effects), the possibility of kinematical reflections in recoil-mass plots, and surprisingly, electromagnetic mass splittings (ems) D^+-D^0 and $D^{*+}-D^{*0}$.

First, we discuss the relative production of D and D^* neglecting their mass differences. Then, we estimate ems, and discuss its impact on D^* decay and on the data analysis. Finally, we take into account the mass differences, obtaining agreement with data, and making predictions about future results.

Quasi-two-body production of D and D.*—Near threshold, pairs of oppositely charmed particles are probably produced in P-wave final states $D\bar{D}$, $D\bar{D}^*+D^*\bar{D}$, and $D^*\bar{D}^*$. The relative production cross sections depend on how quark spins and angular momenta arrange themselves to make mesons. The photon directly produces a pair of charmed quarks, each of which becomes a charmed meson in combination with a subsequently produced u or d quark. The charmed pairs are equally likely to be charged or neutral. (We defer consideration of $F^+=c\bar{s}$ pair production.) Charmed quarks are heavy, so we neglect their spin-dependent couplings to light quarks. Thus, the spin of the charmed quarks $S=S_1+S_2$ is conserved with $S^2=2$, and the spins of light quarks s_i are uncorrelated to the spins of charmed quarks, $\langle s_i S_j\rangle=0$. In a P-wave state of two charmed mesons, $(s_1+s_2)^2=2$. From this we compute that the final states $D\bar{D}$, $D\bar{D}^*+D^*\bar{D}$, and $D^*\bar{D}^*$ are populated in ratios 1:4:7, and that $D\bar{D}$ production is relatively suppressed.

At energies far above threshold, quasi-two-body production is strongly damped by form factors and is a small part of the charm-containing cross section. Nonetheless, we expect the inclusive yield of D^* to be three times that of D in accordance with a counting of spin states.

When D^0 is detected, it may have been produced with $\bar{D}^0$ or $\bar{D}^{*0}$. Or, it may have been the decay product of D^{*+} or D^{*0}. Because the Q values for the $D^*\to D\pi$ modes are very small, estimates of ems are essential to determine branching ratios for $D^{*+}\to D^0\pi^+$, $D^{*0}\to D^0\pi^0$, and $D^{*0}\to D^0\gamma$. These enable us to predict (1) the ratio of cross sections for charged- versus neutral-D production; and, (2) the nature of the recoil spectrum against charged or neutral D's.

Electromagnetic mass splittings.—Consider a crude quark-model description of the meson mass differences $\pi^+-\pi^0$, K^+-K^0, D^+-D^0. Coulomb contributions, δ, are proportional to products of charges of constituent quarks, which are in ratios 3:2:4 for the three splittings. We fit the pion mass splitting (for which there is only a Coulomb term) and assume a common value for $\langle r^{-1}\rangle$ thereby underestimating this contribution for K and D and obtaining $\delta(K^+-K^0)=3$ MeV and $\delta(D^+-D^0)=6$ MeV. Non-Coulomb contributions, δ', result from the d quark being heavier than the u. This makes K^0 heavier than K^+ by the same amount it makes D^+ heavier than D^0. We fit the observed kaon masses to find $\delta'=7$ MeV. *Both effects have the same sign for D's, and we find* $M(D^+)-M(D^0)\geq 13$ *MeV.* Since hfs effects are small for the D system, we assume the same ems for D^*'s, i.e., the value 15 MeV.

Experiment indicates[3] $M(D^0)\cong 1.86$ MeV and $M(D^{0*})\cong 2.00$ GeV.[5] Using our estimate of ems, we tabulate available energies Q and branching ratios B for D^* decays as follows:

$$D^{*+}\to\begin{cases} D^0\pi^+, & Q=15\text{ MeV}, \quad B\sim 90\%,\\ D^+\pi^0, & Q=5\text{ MeV}, \quad B\sim 10\%,\\ D^+\gamma, & Q=140\text{ MeV}, \quad B\sim 1\%,\end{cases}$$

$$D^{*0}\to\begin{cases} D^0\pi^0, & Q=5\text{ MeV}, \quad B\sim 90\%,\\ D^+\pi^-, & Q=-5\text{ MeV}, \quad B\sim 0,\\ D^0\gamma, & Q=140\text{ MeV}, \quad B\sim 10\%.\end{cases}$$

Although none of the masses we use are precisely determined, the point is clear: *Decays of charged or neutral D^*'s predominantly yield D^0's and pions.*

To the extent that $\bar{D}D$, $\bar{D}D^*+\bar{D}^*D$, $\bar{D}^*D^*$ production obeys the predicted 1:4:7 ratios, the yield of neutral D's is expected to be seven times greater than the yield of charged D's. At higher energies where inclusive production is dominant, a 3:1 ratio of D^* to D production persists, as does the 7:1 suppression of charged D's. What is surprising is not that $D^\pm$ has evaded discovery, but that ems cause its suppression.

Threshold effects and form factors.—Consider the recoil spectrum observed when D^0 is detected. Quasi-two-meson production must be corrected for P-wave threshold effects by the factor $x^{3/2}$ where $x=s-(m_1+m_2)^2$. An exponential form factor $e^{-x/\Gamma}$ depending on an adjustable parameter describes a falloff of the two-body process depending only on distance from the appropriate threshold. This crude description is probably adequate to describe the data. It is partly the effect of the form factors that causes the recoil spectrum to change its character with increasing energy as the quasi-two-body process is superceded by inclusive production.

Recoil bumps and kinematical reflections.—When $D^0\bar{D}^0$ is produced and D^0 is detected, the recoil mass peaks at $M(D^0)$. When $D^0\bar{D}^{0*}$ is produced and D^0 is detected, the recoil mass peaks at $M(D^*)$. When $D^{*0}\bar{D}^0$ or $D^{*+}\bar{D}^-$ is produced, the D^* almost always decays into $D^0\pi$. If this secondary D^0 is detected, the recoil mass nonetheless peaks near $M(D^*)$, although with a detectable spread. This is because of the small available energy in D^* decay and (at $s^{1/2}\sim 4.1$ GeV) the proximity of threshold. The predicted recoil-

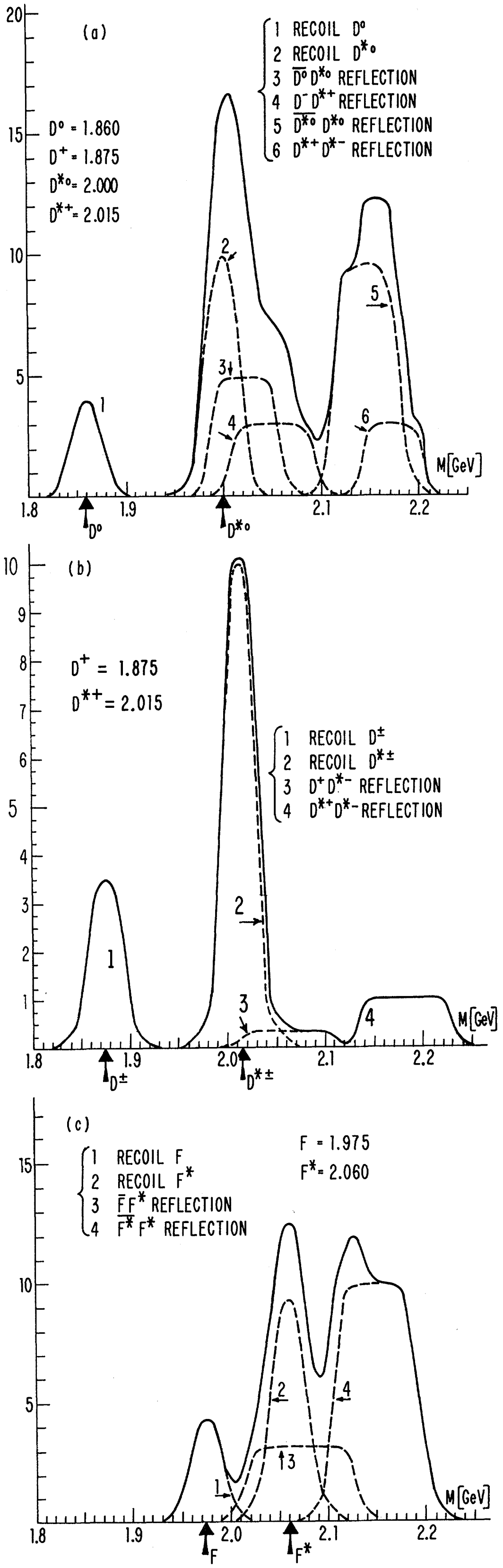

FIG. 1. Spectrum of recoil mass for quasi-two-body production of charmed mesons. Recoil mass against (a) a D^0 at $s^{1/2} = 4.05$ GeV, (b) a $D^\pm$ at $s^{1/2} = 4.1$ GeV, (c) a F^+ at $s^{1/2} = 4.2$ GeV. The ordinate is arbitrary. The solid line is the sum of all contributions to the recoil spectra.

mass peak at ~ 2 GeV is a confluence of two effects: One-third is a sharp recoil peak signifying a recoiling $\bar{D}^{*0}$; the rest is a kinematical reflection wherein the detected D^0 is a D^* decay product.

When $D^*\bar{D}^*$ is produced, D^0 almost always emerges as a decay product. We predict a second relatively narrow peak in the recoil-mass distribution against detected D^0's near $M(D^*) + M(\pi)$. Its existence reflects pair production of D^*'s. It does not indicate a third new state; indeed, the standard theory does not admit the existence of another state at such a low mass.

As s increases, recoil-mass spectra change for two reasons. Peaks due to kinematical reflections broaden, and other processes compete with quasi-two-body charm production.

Recoil spectra.—We compute the expected mass spectrum recoiling against detected D^0's. The result is sensitive to s since thresholds are nearby. We use an effective mean $s^{1/2}$ of 4.05 GeV, appropriate to the data in which the $K\pi$ enhancement is discovered.[6]

The three recoil-mass enhancements (corresponding to $D\bar{D}$, $D\bar{D}^* + D^*\bar{D}$, and $D^*\bar{D}^*$ production) should have areas in the ratios

$$\left.\begin{array}{l} A(1.86) \sim 1 \\ A(2.02) \sim (4+2B) \\ A(2.15) \sim (7+7B) \end{array}\right\} \times x^{3/2}\theta(x)\exp(-x/\Gamma),$$

where B is the branching ratio for $D^{*+} \to D^0\pi^+$. In our calculations we treat separately the several electromagnetic sub-modes since ems plays a role. A fit to the reported recoil structure at 2–2.2 GeV is found with $\Gamma \sim 1$ GeV^2. The resulting spectrum, with experimental resolution of 25 MeV, is shown in Fig. 1(a). A small peak at 1.86 GeV is expected but not yet observed with an area of ~ 8% of the higher-mass recoil structure.

Knowing the relative D and D^* yields at 4.05 GeV, we estimate the suppression of charged D production: We find that 20% of the final-state D's are charged. At higher energies where inclusive phenomena take over, this fraction should decrease to 12.5%.

Sooner or later $D^\pm$ must be found as a peak in $K^\mp\pi^\pm\pi^\pm$. Our predicted recoil-mass spectrum at

$s^{1/2}$ of 4.1 GeV is shown in Fig. 1(b). The structure is displaced to higher energies by ems. According to our estimates, D^{*0} never yields a D^+ decay product, and D^{*+} yields $D^+\pi^0$ 10% of the time. Thus, enhancements due to kinematical reflections are smaller. Thus the relative areas of the three recoil peaks are different in Figs. 1(a) and 1(b).

Our predictions for the masses of $(c\bar{s})$ states F and F^* were 1.975 and 2.06 GeV, so that $F^* \to F\gamma$ electromagnetically. F and F^* produced at ~ 4.2 GeV may be as common as D and D^* at ~ 4.05 GeV, and F may be detected in its $K^\pm K_s$ or $K^+K^-\pi^\pm$ modes. Our prediction for the recoil spectrum against detected F's is shown in Fig. 1(c).

P-wave excitations of D and F are anticipated. Following Ref. 4, we predict a $J^P = 2^+$ excited D at 2.42 ± 0.03 GeV and an excited F at 2.47 ± 0.03 GeV. The study of recoil-mass spectra against detected D^0's or F's at higher s may reveal these states.

Charmed baryons.—We are accustomed to mesons being much more abundant in e^+e^- annihilation than baryons, which probably reflects the fact that nucleons are much heavier than pions. For charmed particles this is not so. The mass of the lightest charmed baryon Λ_c ($J = \frac{1}{2}$, $I = 0$ state of cud) was predicted[4] to be 2.25 ± 0.05 GeV, not so different from the masses of charmed mesons. At $s^{1/2} \sim 4.5$–4.8 GeV, the two-body $\Lambda_c\bar{\Lambda}_c$ final state may be copiously produced. Possible decay modes of Λ_c include pK_s and $\Lambda\pi^+$. Such a peak should be searched for, and the recoil-mass distribution should show a single clear peak at $M(\Lambda_c)$

The "hyperfine partners" of Λ_c, $I = 1$ states with $J = \frac{1}{2}$ and $J = \frac{3}{2}$, should be 150–250 MeV heavier,[4] and should decay strongly into $\Lambda_c\pi$. At higher $s^{1/2}$, say 4.8–5.4 GeV, the yield of Λ_c as decay products of these isovector states may be significant. If Λ_c is detected, measurement of the recoil-mass spectrum should show structure due to kinematical reflections of the heavier states. $\Lambda\pi^+$ spectroscopy can reveal the whole family of singly charmed nonstrange baryons.

Three isotopic doublets of charm 1, strangeness −1 baryons are expected. The lightest state, predicted at 2.4–2.5 GeV, should decay into two-body channels ΛK_s, $\Xi\pi$, and $\Sigma^+\bar{K}$. At $s^{1/2} \sim 4.8$–5.6 GeV, a significant yield due to quasi-two-body production of charmed strange baryons is likely. Once a peak is found, a study of recoil masses can reveal the other states.

In summary, it may be fruitful to search for charmed states—both mesons and baryons—at e^+e^- energies of 4–6 GeV. Peaks in invariant masses of several final hadrons are expected, accompanied by rich and energy-dependent structure in the recoil-mass spectra. Dozens of new hadrons await discovery.

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