Evidence for the F^* Meson

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Evidence for a narrow state decaying into an F meson and a photon has been obtained in e^+e^- annihilation events at 29-GeV c.m. energy. This state lies 139.5 ± 8.3(stat.) ± 9.7(syst.) MeV above the F-meson mass and is consistent with the expected F^* meson. The F mesons are identified by a peak in the $K^+K^-K\pi^\pm$ mass at $1.948 \pm 0.028 \pm 0.010$ GeV.

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The quark model predicts four ground-state charmed mesons[1]: D, D^*, F, and F^*. The first three of these are now well established,[2-4] and searches for the F^* have been conducted by several experiments,[5] with the first candidates reported recently.[6] According to the quark model, the F^* and the F are isosinglets and the $F^* \rightarrow F\pi^0$ decay is forbidden leaving the radiative decay to the F as the only significant mode.

We report evidence for a narrow state that decays to an F meson and a monochromatic photon using data collected by the PEP-4 TPC detector at the PEP storage ring at SLAC. Our observation is based on 29 095 hadronic events (corresponding to an integrated luminosity of 77 pb^{-1}) produced in e^+e^- annihilation at $E_{\text{c.m.}} = 29$ GeV.

In the PEP-4 detector,[7] momentum and ionization loss (dE/dx) of charged particles are measured in a time projection chamber (TPC). In the TPC, the dE/dx value for each track is calculated from the pulse heights measured by anode wires of multiwire proportional chambers.[8] The average dE/dx resolution is 3.9% for tracks with at least thirty ionization samples. At a momentum of 5 GeV/c, typical for this analysis, the measured π-K separation in dE/dx is 14%. The momentum resolution is given by $(dp/p)^2 \simeq (0.06)^2 + (0.035p)^2$ (p in GeV/c) for tracks in hadronic jets.

Photons are detected either by the hexagonal Geiger-mode calorimeter, or by the TPC as e^+e^- pairs arising from photon conversion. In the calorimeter the photon energy is measured to about $16\%/\sqrt{E}$ (rms with E in gigaelectronvolts) and nearby pairs of photons are resolved if the angle between them is greater than 60 mrad. Photons are accepted if their polar angle θ is between 50° and 130° and if their energy is greater than 400 MeV in the calorimeter. Photons of any energy are accepted if they convert in front of the TPC, and the conversion pair is unambiguously identified. Of photons contained in the solid angle and energy range defined by the selection criteria, 41% are detected in the calorimeter and 8% are detected in the TPC as conversion pairs.

With the use of the measured momentum and dE/dx, χ^2's are calculated for each track to be an electron (χ_e^2), a pion (χ_π^2), a kaon (χ_K^2), or a proton (χ_p^2). A particle is then "identified" as a kaon if (a) the number of good dE/dx sample points is 30 or more, (b) $\chi_K^2 < 2.7$ (for one degree of freedom), and (c) $\chi_K^2 < \chi_e^2, \chi_\pi^2, \chi_p^2$ if $p < 2$ GeV or $\chi_K^2 < \chi_e^2, \chi_\pi^2$ if $p > 2$ GeV/c. A looser criterion, $\chi_\pi^2 < 6.6$, is used for pions since the level of background from kaon misidentification is small.

In each hadronic event the invariant mass, $M(KK\pi)$, is calculated for all possible $K^+K^-\pi^\pm$ combinations. A cut is made on the total $KK\pi$ energy fraction, $z=E/E_{\rm beam}>0.45$. The $M(KK\pi)$ distribution for this data sample is shown in Fig. 1(a). A possible enhancement is seen around the F mass, 1.97 GeV.

All $KK\pi$ combinations are kinematically fitted to a mass of 1.97 GeV (a one-constraint fit). Those combinations for which the fit yields a good χ^2 (C.L. > 10%) constitute an F-candidate sample. Photons in these events are added to the mass-constrained $KK\pi$ combinations and the $KK\pi\gamma$ invariant mass is computed. For those combinations with $z=E(KK\pi\gamma)/E_{\rm beam}>0.5$, the mass-squared difference, $\Delta M^2=M^2(KK\pi\gamma)-M^2(KK\pi)$, is calculated and shown in Fig. 2 (solid line). Here ΔM^2 is used because it depends linearly on the measurement error in the photon energy. When there is more than one F-candidate combination for a given photon, each entry in the ΔM^2 histogram is weighted by the reciprocal of the number of candidates for that photon. A ΔM^2 control distribution is obtained by selecting $KK\pi$ combinations that give a good fit (C.L. > 10%) when the mass is constrained either to 1.67 GeV (control mass 1) or to 2.27 GeV (control mass 2) but give a poor fit (C.L. < 1%) to a mass of 1.97 GeV. A photon is then combined with the mass-constrained $KK\pi$. The ΔM^2 spectrum for $KK\pi\gamma$ combinations in the F-candidate sample shows a peak, while the control distribution reveals no structure (dashed line in Fig. 2).

Our Monte Carlo event generator has been updated to reproduce the known branching fractions of D and D^* mesons.[4] Special care has been taken to model dE/dx behavior correctly so as to enable accurate estimation of particle-misidentification probabilities. For momenta between about 1.0 and 1.5 GeV/c, the energy lost by kaons through ionization is nearly the same as that for pions, making π-K separation difficult or impossible. Generated distributions indicate that, in the absence of an F^* meson, the shape of the ΔM^2 distribution in the F region is very similar to that obtained for the control sample, both distributions having a smooth, structureless shape.

We simultaneously fitted both the F-candidate and control ΔM^2 distributions to a smooth background, plus, for the F-candidate sample, a Gaussian peak. The width of the peak is fixed to the value (0.13 GeV^2 rms) given by the Monte Carlo calculation for a monochromatic photon whose energy is smeared by detector resolution. The best fit gives $\Delta M^2=0.569\pm0.037(\text{stat.})\pm0.041(\text{syst.})$ GeV^2 with 60 ± 15 events in the peak. Under the assumption that the F mass is 1.97 GeV,[3] the corresponding mass difference is

$$\Delta M=139.5\pm8.3\pm9.7\text{ MeV}.$$

The invariant-mass distribution (without any constrained fitting) of all $K^+K^-\pi^\pm$ combinations is shown in Fig. 1(b) for those with the unconstrained mass-squared difference in the region of the ΔM^2 peak, namely $0.4<\Delta M^2<0.8$ GeV^2 (solid line), and in a control region, $0.9<\Delta M^2<1.3$ GeV^2 (dashed line). For the combinations in the ΔM^2 peak region, a peak is seen near the

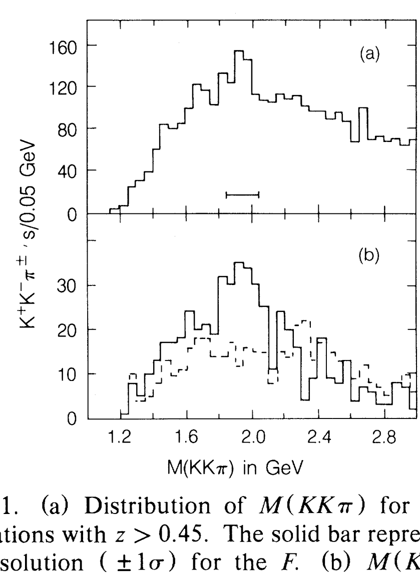

FIG. 1. (a) Distribution of $M(KK\pi)$ for all $KK\pi$ combinations with $z>0.45$. The solid bar represents our mass resolution ($\pm1\sigma$) for the F. (b) $M(KK\pi)$ for $K^+K^-\pi^\pm\gamma$ combinations with $0.4<\Delta M^2<0.8$ GeV^2 (solid line) and for those with $0.9<\Delta M^2<1.3$ GeV^2 (dashed line).

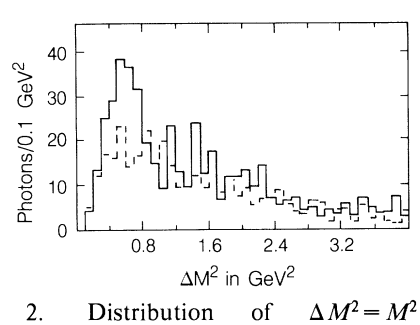

FIG. 2. Distribution of $\Delta M^2=M^2(KK\pi\gamma)-M^2(KK\pi)$: The solid line is that of the F-candidate sample and the dashed line is the average of the distributions for control masses 1 and 2 (see text).

known F mass, while no peak is seen for those in the control region. A fit is made to this distribution, using a smooth background shape plus a Gaussian peak. Again, the width is fixed to that predicted by the Monte Carlo calculation due to detector resolution (85 MeV). The resulting peak is at $M(KK\pi) = 1.948 \pm 0.028 \pm 0.010$ GeV and contains 65 ± 17 events.

We consider various sources of the peak in the ΔM^2 distribution. A possible source is random combinations of charged particles, correctly, or incorrectly identified, and photons. As mentioned above, our Monte Carlo calculation tuned to the best of our ability, produces no such peak, nor have we been able, by varying particle identification criteria, photon momentum requirements, or detector resolutions, to produce a peak in the distribution without including an F^* meson.

Since the various charmed-meson branching fractions are not known precisely, various possible modes must be examined separately to determine whether, with an increased branching fraction, they might explain the peak. We have examined the following decays: (1) $D^{*+} \to D^+\pi^0/\gamma$ with $D^+ \to K^-\pi^+\pi^+$; (2) $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\rho^+$ and $\rho^+ \to \pi^+\pi^0$, in which we have included spin alignment in the decay distributions; and (3) $D^{*0} \to D^0\pi^0/\gamma$ with $D^0 \to K^-\pi^+ + X$. These decays could contaminate our F-candidate sample if a pion is misidentified as a kaon. With use of the branching fractions given by Wohl *et al.*,[4] our Monte Carlo calculation indicates that none of these contributes more than three events to the ΔM^2 peak, nor could modes (1) or (2) produce a peak in the appropriate location in the ΔM^2 plot. Similarly, contributions from charmed baryons are found to be negligible.

We are led to the conclusion that the ΔM^2 peak is due to the decay $F^* \to F\gamma$. The peaks in both the ΔM^2 and $M(KK\pi)$ distributions have widths that are consistent with those due to detector resolution, and the peak in the $M(KK\pi)$ distribution is at a mass consistent with that of the F.

We next consider which decay modes of the F^+ we are observing, the most likely modes being $K^+K^-\pi^+$, $\bar{K}^{*0}K^+$, and $\phi\pi^+$. The KK mass spectrum of $KK\pi\gamma$ combinations in the ΔM^2 peak indicates that $\phi\pi^+$ is not the dominant mode, but the $K^-\pi^+$ mass spectrum is inadequate to determine the rates to $K^+K^-\pi^+$ and $\bar{K}^*K^+$. Modes producing only a pair of kaons and a pion, however, are not the only possibilities. Because of the poor $KK\pi$ mass resolution, some events from modes in which a particle is missing (e.g., $K^+K^-\pi^+\pi^0$, or $K^+K^-\mu^+\nu$, in which the muon is called a pion) would produce a similarly narrow peak in the ΔM^2 distribution. Monte Carlo studies indicate that acceptances for such modes are roughly half of that for $K^+K^-\pi^+$. The observed momentum spectra of the decay products of the F candidates are not well reproduced by a Monte Carlo program in which the $F \to K^+K^-\pi^\pm$ decay occurs uniformly over phase space. The shape of the $M(KK\pi)$ distribution, however, is consistent with $K^+K^-\pi^+$ being the dominant mode.

With the proviso that by "$K^+K^-\pi^+$" we include other modes such as those listed above, we proceed to obtain a value for $\sigma_{F^*}R_B(F^+ \to$ "$K^+K^-\pi^+$"), where σ_{F^*} $(= \sigma_{F^{*+}} + \sigma_{F^{*-}})$ is the F^* production cross section and R_B is the branching fraction to the mode in parentheses. The acceptance for $F^{*\pm} \to F^\pm\gamma \to K^+K^-\pi^\pm\gamma$, as determined by Monte Carlo calculation, is found to be about 6% for $0.4 < z < 1.0$. From the experimental F^* yield we get,

$$\sigma_{F^*}(z > 0.4)R_B(F^+ \to \text{“}K^+K^-\pi^+\text{”})/\sigma_h = (3.34 \pm 0.95 \pm 1.11) \times 10^{-2},$$

in which σ_h is the hadronic cross section.

We calculate the observed cross section as a function of z (Fig. 3) and fit to the fragmentation function of Peterson *et al.*[9] We find $\epsilon_c = 0.19^{+0.17}_{-0.08}$ which is consistent with the values found for D and D^*.[10] We obtain the integrated cross section

$$\sigma_{F^*}R_B(F^+ \to \text{“}K^+K^-\pi^+\text{”})/\sigma_h = (3.6 \pm 1.0 \pm 1.2) \times 10^{-2}.$$

If the ratio of probabilities to create pairs of u, d, and s quarks from the vacuum is assumed to be 1:1:0.3 and if the probability for a $c\bar{s}$ pair to become an F^* meson is taken to be unity, and if the creation of F^*'s by b quarks can be neglected, we obtain a branching fraction to the mode(s) we see of

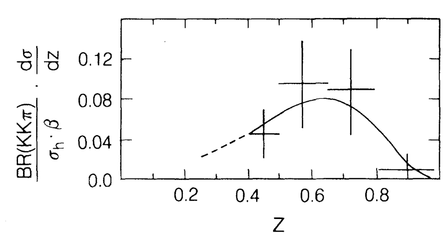

FIG. 3. Inclusive differential cross section of F^* production vs z $(= E_{F^*}/E_{\text{beam}})$. The curve is the best fit to the Peterson fragmentation function (Ref. 9).

$R_B(F^+ \rightarrow$ "$K^+K^-\pi^+$"$) = (38 \pm 11 \pm 13)\%$; which can be converted to an upper limit of the branching fraction to $K^+K^-\pi^+$.

We have studied the $M(K^+K^-)$ distribution to estimate the $R_B(F^+ \rightarrow \phi\pi^+)$. We get a 90% C.L. upper limit to the branching fraction, $R_B(F^+ \rightarrow \phi\pi^+) < 13\%$. This is consistent with previous experiments.

We conclude that we have obtained evidence for the F^* meson decaying to $F\gamma$. The F^*-F mass difference is $139.5 \pm 8.3 \pm 9.7$ MeV. The F meson is identified as a peak in the invariant-mass distribution of $K^+K^-\pi^\pm$ in coincidence with a monochromatic photon.

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