Evidence for new charm mesons near 1800 MeV

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A review of $X^+ \to \phi\pi^+$ events from e^+e^- annihilation, photoproduction, and hadroproduction, and of events in the related decay channels $\bar{K}^{*0}K^+$ and nonresonant $K^+K^-\pi^+$ from photoproduction and hadroproduction, provides evidence for a charged particle near 1800 MeV. A review of $X^0 \to K^-\pi^+$ events from e^+e^- annihilation and photoproduction provides evidence for a neutral particle near 1785 MeV. The signal widths are comparable with the spectrometer resolutions. More significantly, both particles have been observed at secondary vertices in lifetime experiments, suggesting that their lifetimes are comparable with charm lifetimes. It is hypothesized that they may be strongly bound composite charm mesons.

INTRODUCTION

It is difficult to isolate the signals for charmed hadrons produced in photoproduction, hadroproduction and e^+e^- experiments. An enormous background of ordinary and strange hadrons obscures the relatively small charm signal. Typically the decay products of millions of events must be sifted to filter out a few tens of desired charm events, and much ingenuity has been applied to designing data cuts that can selectively eliminate unwanted events. When all goes well a signal can be reconstructed in an invariant-mass plot where the remaining random background events are washed out by failure to aggregate at any particular mass value. False signals from decay products that are misidentified and assigned the wrong masses are distinguishable from true signals and can be rejected because they tend to spread out over a relatively wide range of mass values. False signals that result from missing neutral decay products tend also to be broadened and lost in the random background.

In addition to the noncoherent random background, coherent extraneous signals can arise from unsought particles that happen to share the same decay channel as a particle under study. These signals can identify themselves by aggregation at appropriate invariant-mass values, or can be reduced to insignificance by data cuts designed to discriminate against them. Because data collection and analysis are time consuming and expensive, charm-meson experiments have tended to accumulate data only for particles known or strongly presumed to exist, and only to the point where the magnitude of the sought-after signal becomes statistically significant. Under these conditions the signals from unsuspected and unsought particles, viewed as noise and where possible discriminated against by data cuts, tend to be statistically insignificant.

Yet traces of signals from other particles can remain, buried in the background to a greater or lesser degree. Even when no single experiment is adequate it is possible that an unexpected particle could be found through aggregating the results of a number of different experiments exploring a common decay channel.

D_s^+ mesons have been extensively studied in the decay channel $D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$ and in related channels. In each of these investigations the invariant mass shows a strong D_s^+ signal near 1970 MeV. (Reference to a state implies reference also to its charge conjugate.) Signals at other mass values would indicate other mesons sharing the same decay channels. Except for the D^+ no other meson has been claimed, although ARGUS [1] data suggest a narrow state near 1800 MeV as shown in Fig. 1. Further evidence for this state is provided by TPS [2] as shown in Fig. 2 and by Mark III [3] in Fig. 3. The excursions in these figures are significant at about the 3.5σ, 2.8σ, and 2.9σ levels, respectively.

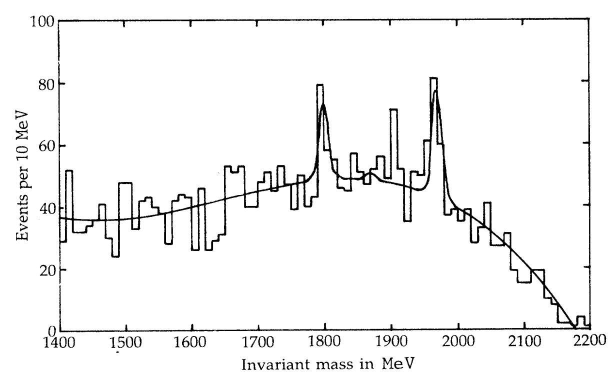

FIG. 1. Invariant masses for $X^+ \to \phi\pi^+$ events from e^+e^- annihilation. Combined data from Figs. 2(a), 2(b), and 2(c) of ARGUS [1] for which an associated photon was required with $E_\gamma^{\rm lab} > 110$ MeV and with $\phi\pi\gamma$ invariant mass in the range 1990–2260 MeV. Fit with Gaussians of equal width at 1800, 1870, and 1970 MeV and a cubic polynomial background. A signal at 1800 MeV is suggested.

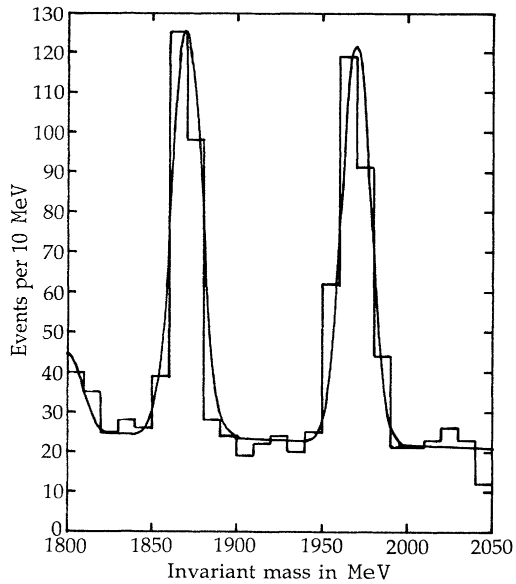

FIG. 2. Invariant masses for $X^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, and $K^+K^-\pi^+$ events from photoproduction. Combined data from Figs. 5(a), 5(b), and 5(c) of TPS [2]. Fit with Gaussians of equal width at 1800, 1870, and 1970 MeV and a linear background. A signal at 1800 MeV is suggested.

D^0 mesons have been extensively studied in the decay channel $D^0 \to K^-\pi^+$. In each of these investigations the invariant mass shows a strong D^0 signal near 1865 MeV. No other meson has been claimed although TPS [4] data suggest a narrow state near 1785 MeV as shown in Fig. 4. The excursion in this figure is significant at the 5.2σ level.

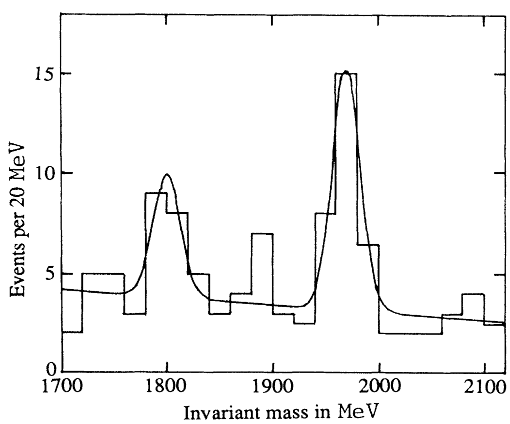

FIG. 3. Invariant masses for $X^+ \to \phi\pi^+$ events from e^+e^- annihilation. Data from Fig. 2 of Mark III [3], a scatterplot with $\phi\pi$ mass along the horizontal axis and recoil mass along the vertical axis. Data in a 220-MeV band at the upper boundary of recoil mass are projected into 20-MeV bins along the $\phi\pi$ mass axis. This data cut avoids $\bar{D}$ and $\bar{D}^*$ recoiling from D and as a result no D signal is expected. Fit with Gaussians of equal width at 1800 and 1970 MeV and a linear background. A signal at 1800 MeV is suggested.

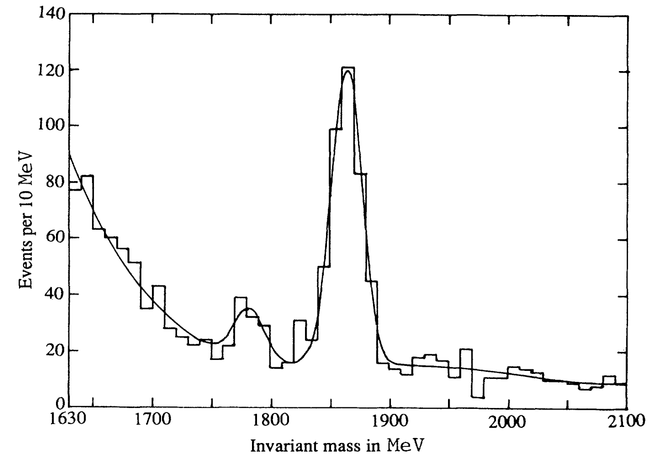

FIG. 4. Invariant masses for $K^-\pi^+$ events from photoproduction. Data for $\Delta z/\sigma_z = 12$ from Fig. 8(d) of TPS [4]. Fit with a quartic polynomial background plus Gaussians of equal width at the experimental D^0 peak and at the excursion near 1785 MeV. A signal near 1785 MeV is suggested.

The coincidence of excursions near 1800 MeV in $\phi\pi^+$ experiments and the magnitude of the excursion near 1785 MeV in the $K^-\pi^+$ experiment suggest the possibility of new mesons at these masses. In the following sections this possibility is examined by review of evidence from published data and by an assessment of its statistical significance. A case emerges for new stable mesons, tentatively interpreted as strongly bound composites.

EVIDENCE FROM $\phi\pi^+$ AND RELATED MASS PLOTS

Evidence was sought in a review of articles cited by the Particle Data Group [5] and of additional articles published through 1989. (The $\phi\pi^+$ mass plots published in more recent articles tend to derive from the same or enhanced data bases as employed in earlier work, and for this reason often do not constitute independent evidence.) Although angular data cuts have been employed in some D_s^+ experiments to reduce the number of background

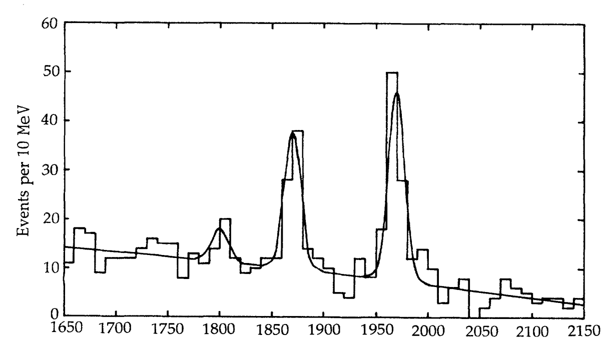

FIG. 5. Invariant masses for $X^+ \to K^+K^-\pi^+$ events from (K^-,π^-)Cu hadroproduction. Data from Fig. 1(b) of ACCMOR [6]. Fit with Gaussians of equal width at 1800, 1870, and 1970 MeV and a cubic polynomial background. A signal at 1800 MeV is suggested.

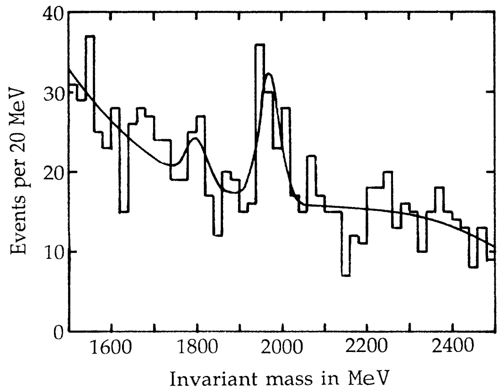

FIG. 6. Invariant masses for $X^+ \rightarrow \phi\pi^+$ events from e^+e^- annihilation. Data from Fig. 2(a) of TASSO [7]. Fit with Gaussians of equal width at 1800 and 1970 MeV and a cubic polynomial background. A signal at 1800 MeV is suggested.

events from spin-1 contaminants, such cuts were not employed for the mass plots in Figs. 1–3. For consistency, and to leave open the possibility of nonzero spin, the review was restricted to experiments that did not specify angular cuts. Mass plots from all those found are shown in Figs. 1–3 and 5–11. These constitute the full data set where D_s^+ signals have been reported in the $K^+K^-\pi^+$ channel and in related resonant subchannels. Excursions near 1800 MeV are universally present.

STATISTICAL SIGNIFICANCE

Particular care must be taken in the process of evaluating significance through cumulative coincidence of a

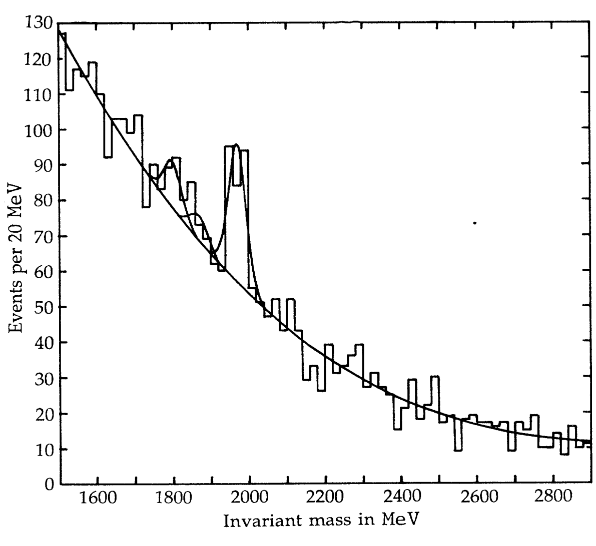

FIG. 7. Invariant masses for $X^+ \rightarrow \phi\pi^+$ events from e^+e^- annihilation. Data from Fig. 2(a) of CLEO [8]. Fit with Gaussians of equal with at 1800, 1870, and 1970 MeV and a cubic polynomial background. For clarity because there is some overlap, the three Gaussians are shown individually relative to the common background. A signal at 1800 MeV is suggested.

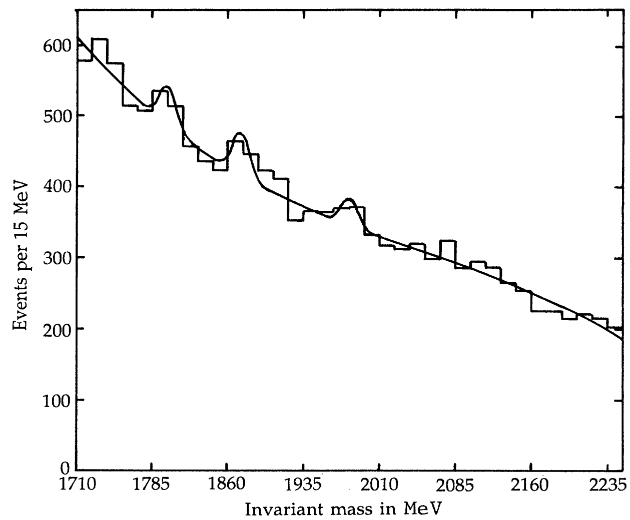

FIG. 8. Invariant masses for $X^+ \rightarrow \phi\pi^+$ events from *nBe* hadroproduction. Data from Fig. 2 of Shipbaugh *et al.* [9]. Fit with Gaussians of equal width at 1800 MeV and (to conform with Shipbaugh *et al.*) at 1873 and 1981 MeV, and a cubic polynomial background. A signal at 1800 MeV is suggested.

number of small signals. There must be no bias in the selection of data. A fictitious significance can always be created out of nothing when experiments with negative fluctuations are ignored and attention is confined to those with positive fluctuations. It is essential that all published data in a given class be considered without exception. Even here there is a possibility for introducing bias by tailoring the selection criteria in a nonphysical way to favor data with positive fluctuations. This possibility can be minimized by restricting the selection criteria to those that can be understood on objective grounds. The data

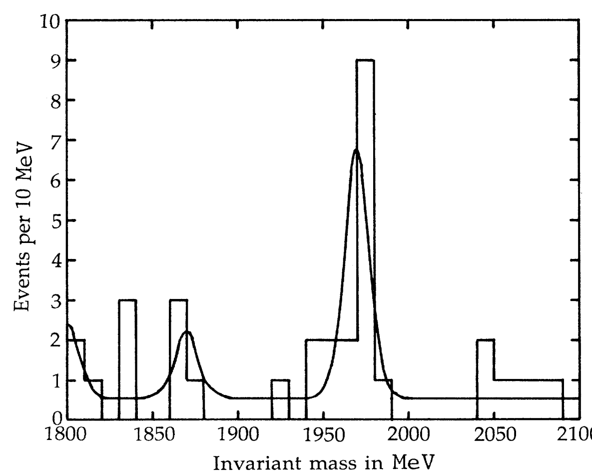

FIG. 9. Invariant masses for $X^+ \rightarrow \phi\pi^+$, $\bar{K}^{*0}K^+$, and $K^+K^-\pi^+$ events from K^-Si hadroproduction. Data from Fig. 3(d) of ACCMOR [10]. Fit with Gaussians of equal width at 1800, 1870, and 1970 MeV and a constant background. A signal at 1800 MeV is suggested.

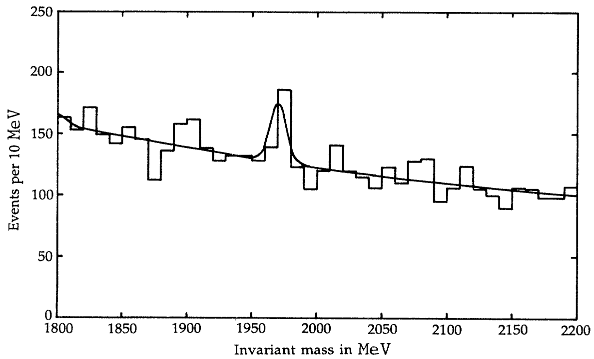

FIG. 10. Invariant masses for $X^+ \to \phi\pi^+$ events from e^+e^- annihilation. Combined data from upper histograms of Figs. 3(a) and 3(b) of HRS [11]. Fit with Gaussians of equal width at 1800 and 1970 MeV and a quadratic background. There is a hint of a signal at 1800 MeV.

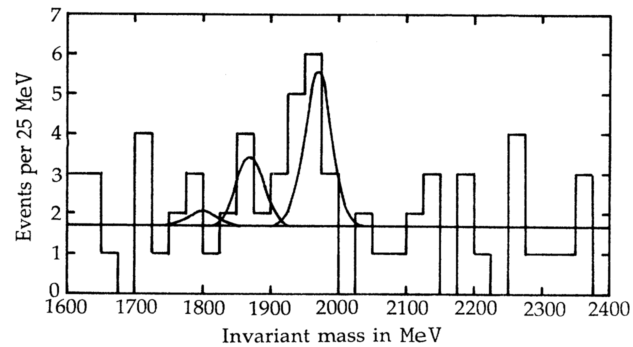

FIG. 11. Invariant masses for $X^+ \to \phi\pi^+$ events from e^+e^- annihilation. Data from Fig. 1(b) of TASSO [12], representing results from a new data set independent of that in Ref. [7]. Fit with Gaussians of equal width at 1800, 1870, and 1970 MeV and a constant background. For clarity because there is some overlap, the three Gaussians are shown individually relative to the common background. There is a hint of a signal at 1800 MeV.

set summarized in Figs. 1–3 and 5–11, constituting mass plots for all known D_s^+ experiments published through 1989 exploring the $K^+K^-\pi^+$ decay channel and related resonant subchannels, and not employing angular data cuts that discriminate against spin-1 mesons, is believed to be free from bias.

The curves in Figs. 1–3 and 5–11 have been fit with Gaussians centered at 1800 MeV as is appropriate for analysis of mesons presumed to exist at that mass. However the presumption of a signal can bias interpretation in favor of a signal, and in establishing the significance of excess events at 1800 MeV it is preferable to test the data on the hypothesis that there is no signal. Curves fit on this hypothesis were published by the authors of eight of the ten mass plots (Figs. 2, 5–11), and have been calculated for the other two (Figs. 1 and 3) using the prescriptions given in their figure captions but omitting Gaussians at 1800 MeV. For these unbiased background curves the excess events in the mass bins nearest 1800 MeV, in which the preponderance of signal events would be expected if a meson in fact existed at this mass, were compared with the background events in the same bins. A full description of the bin selection criteria is given in the heading of Table I.

Because the ARGUS excursion in Fig. 1 was the first to be noticed and could in principle have arisen from a statistical fluctuation, no significance is attributed to it beyond the fact that it directs our attention to the possibility of a signal at 1800 MeV. Confirmation of this possibility is sought in the nine other experiments, and its significance is determined by the magnitudes of the nine

TABLE I. Statistical significances of the excursions at 1800 MeV in Figs. 1–3 and 5–11. For these estimates the least-squares curves in the figures are not used. Instead least-squares curves are fit with a smooth background plus Gaussians only for D_s^+ and where appropriate for D^+, an approach that does not presume a signal at 1800 MeV. For Figs. 2 and 5–11 such curves were published by their respective authors, and for Figs. 1 and 3 they were calculated as described in Figs. 1 and 3 captions but omitting the Gaussians at 1800 MeV. The significances of the excursions at 1800 MeV were estimated by selecting those mass bins whose centers fell within a half Gaussian width (HWHM) of 1800 MeV using the width determined for the D_s^+ peak, then considering the excess events in these bins over the background events as determined by the least-squares fit. Omitting the ARGUS data that initially directed attention to the possibility of a signal at 1800 MeV, the significances of the nine other excursions range from $+2.6\sigma$ to 0.0σ. The joint probability that all nine could result from independent statistical fluctuations is about 10^{-5}.

Figure	Mass range (MeV)	Ratio of excursion to background	Excursion in units of σ
1. ARGUS [1]	1790–1810	38/99	+3.8
2. TPS [2]	1800–1810	12/28	+2.3
3. Mark III [3]	1780–1820	7/10	+2.2
5. ACCMOR [6]	1795–1805	12/22	+2.6
6. TASSO [7]	1780–1820	10/42	+1.5
7. CLEO [8]	1780–1820	22/159	+1.7
8. Shipbaugh [9]	1785–1815	54/996	+1.7
9. ACCMOR [10]	1800–1810	1/1	+0.6
10. HRS [11]	1800–1810	6/157	+0.5
11. TASSO [12]	1775–1825	0/5	0.0

other excursions. As summarized in Table I these excursions are $+2.3\sigma$, $+2.2\sigma$, $+2.6\sigma$, $+1.5\sigma$, $+1.7\sigma$, $+1.7\sigma$, $+0.6\sigma$, $+0.5\sigma$, and 0.0σ. None by itself is statistically compelling. Yet the joint probability that all nine could arise as independent statistical fluctuations is only about 10^{-5}. They are unlikely to have occurred by chance, and the statistical fluctuation hypothesis appears to be untenable. Another interpretation of the ARGUS signal must be sought.

The narrow widths and universal presence of the signals at 1800 MeV in a wide range of experiments with different production and detection methods makes it improbable that a coincidence of decay product misidentifications or other systematic errors could be responsible. An unanticipated particle sharing the decay channel with D_s^+ seems to be the most likely interpretation.

EVIDENCE FROM $K^-\pi^+$ EXPERIMENTS

The TPS Collaboration [4] has published data for $X^0 \rightarrow K^-\pi^+$ in photoproduction experiments to illustrate the power of their $\Delta z/\sigma_z$ data cut. Here Δz is the component of the distance between primary and secondary vertices along the beam direction, and σ_z is the uncertainty of vertex position. On average, the larger $\Delta z/\sigma_z$ the greater the distance between primary and secondary vertices and the longer the elapsed time for the primary meson. Hence $\Delta z/\sigma_z$ is a surrogate for time, and short-lived events can be eliminated by a data cut that accepts only those events with large $\Delta z/\sigma_z$.

For their illustrative purpose, TPS relaxed the constraints on other data cuts and retained a relatively large background which was reduced in several steps by cuts at progressively larger values of $\Delta z/\sigma_z$. Long-lived mesons are expected to survive these cuts and their signals should emerge and increase in significance as the background is reduced. As shown in Figs. 12, 13, 14, and 2 a signal emerges near 1785 MeV. As summarized in Table II it reaches a statistical significance of 5.2σ at the largest $\Delta z/\sigma_z$ cut.

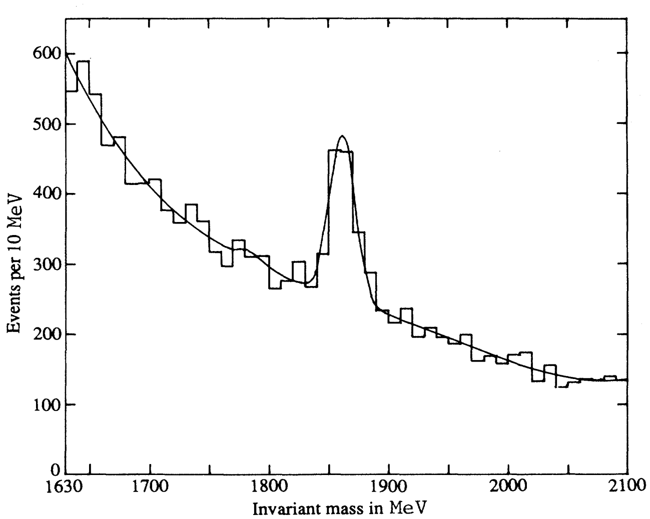

FIG. 12. Invariant masses for $K^-\pi^+$ events from photoproduction. Data for $\Delta z/\sigma_z=3$ from Fig. 8(a) of TPS [4]. Fit with a quartic polynomial background plus Gaussians of equal width at the experimental D^0 peak and at the excursion near 1785 MeV. There is a hint of a signal near 1785 MeV.

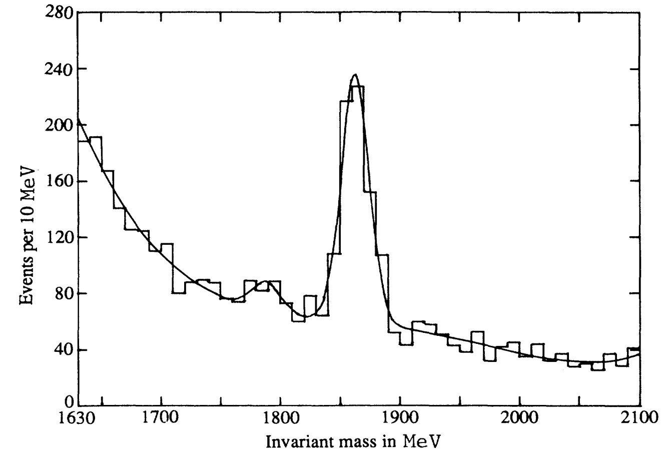

FIG. 13. Invariant masses for $K^-\pi^+$ events from photoproduction. Data for $\Delta z/\sigma_z=6$ from Fig. 8(b) of TPS [4]. Fit with a quartic polynomial background plus Gaussians of equal width at the experimental D^0 peak and at the excursion near 1785 MeV. A signal near 1785 MeV is suggested.

Because $\Delta z/\sigma_z$ is a surrogate for time, we expect the D^0 and $X(1785)^0$ signals to decline as $\Delta z/\sigma_z$ increases. The relative rates of decline are compared in Fig. 15 where it is evident that the lifetime of $X(1785)^0$ is several times longer than the lifetime of D^0.

Further evidence for $X(1785)^0 \rightarrow K^-\pi^+$ was sought in a review of published data.

Many $D^0 \rightarrow K^-\pi^+$ experiments employ D^0 mesons

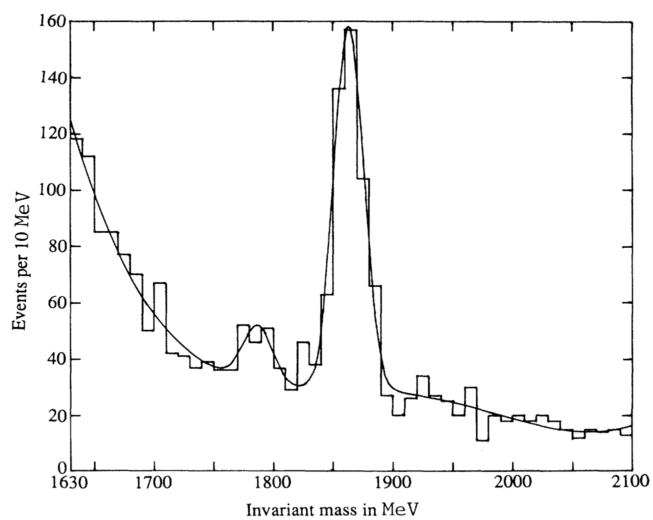

FIG. 14. Invariant masses for $K^-\pi^+$ events from photoproduction. Data for $\Delta z/\sigma_z=9$ from Fig. 8(c) of TPS [4]. Fit with a quartic polynomial background plus Gaussians of equal width at the experimental D^0 peak and at the excursion near 1785 MeV. A signal near 1785 MeV is suggested. (See Fig. 4 for $\Delta z/\sigma_z=12$.)

TABLE II. Selected parameters for the Gaussians fit to the excursions near 1785 MeV interpreted as signals for $X(1785)^0$ mesons, and to the D^0 signals near 1865 MeV, in Figs. 2 and 12–14. As described in the text the parameter $\Delta z/\sigma_z$ is a surrogate for time.

$\Delta z/\sigma_z$	$M(X^0)$	$n(X^0)$	$n(D^0)$
3	1784±33	31±41	618±37
6	1788±9	62±20	522±19
9	1787±6	62±14	390±13
12	1782±6	55±10.5	334±10
	1785±4		

generated from $\psi(3770)$ decay in the reaction chain $e^+e^- \to \psi(3770) \to \bar{D}^0 D^0$ followed by $D^0 \to K^-\pi^+$. Here the D^0 energy must equal the beam energy E_b, making possible a precision data cut where first the $K^-\pi^+$ energy is required to lie close to the beam energy, after which the invariant $K^-\pi^+$ mass is inferred from $(E_b^2 - p^2)^{1/2}$ where p is the $K^-\pi^+$ momentum. This data cut is effective for investigating D mesons because $\psi(3770) \to \bar{D}D$ is the only hadronic channel available. For $X(1785)$ mesons new channels open up. In addition to $\psi(3770) \to \bar{X}X(3570)$ there is the three-product channel $\psi(3770) \to \bar{X}X\pi(3710)$ and as suggested in the section on interpretation there is very likely a two-particle channel to particles of unequal mass $\psi(3770) \to \bar{X}^*X(\sim 3650)$ followed by $X^* \to X\gamma$. In these channels the energies of

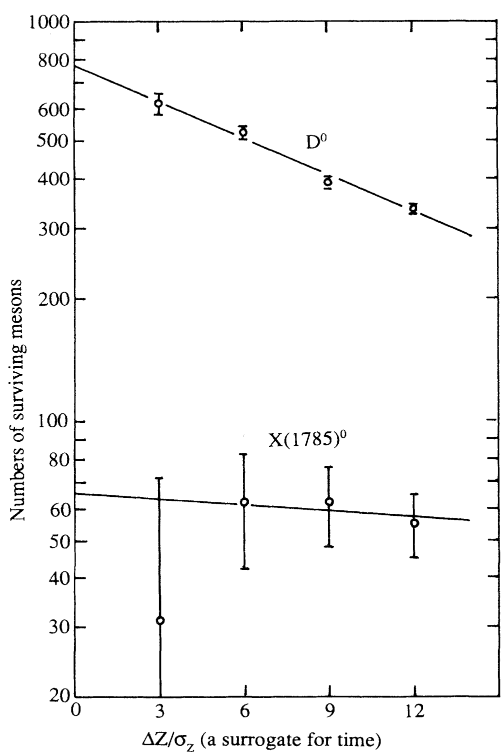

FIG. 15. Decay of D^0 and $X(1785)^0$ mesons with $\Delta z/\sigma_z$ as a surrogate for time. Data from Table II. The lifetime of $X(1785)^0$ is several times longer than the lifetime of D^0.

the $\bar{X}$ and X mesons are not equal to the beam energy, and the beam-constrained energy cut eliminates or smears out the signals for their invariant masses. The new channels are expected to dominate the decay of $\psi(3770)$ to products that include $X(1785)$, and as a consequence $\psi(3770)$ experiments employing the beam energy cut are not expected to provide evidence relating to $X(1785)$.

Other $D^0 \to K^-\pi^+$ experiments employ D^0 generated in the reaction chain $D^{*+} \to D^0\pi^+$ followed by $D^0 \to K^-\pi^+$, overall $D^{*+} \to K^-\pi^+\pi^+$. The mass difference $[M(D^{*+}) - M(D^0)] = 145.5$ MeV is accurately known, making possible a very effective data cut wherein $K^-\pi^+$ candidates are rejected unless they occur in association with an additional π^+ such that $[M(K^-\pi^+\pi^+) - M(K^-\pi^+)] \approx 145.5$ MeV. Any $X(1785)^0$ mesons that might be present would be eliminated by this cut (except in the improbable circumstance that an X^{*+} were to exist for which $[M(X^{*+}) - M(X^0)] \approx 145.5$ MeV). Hence these experiments are unlikely to provide evidence relating to $X(1785)^0$.

Most of the remaining $D^0 \to K^-\pi^+$ experiments employ a high-momentum data cut that eliminates low-momentum events. This cut can be explicit or it can be implicit by tightening an impact-parameter cut. In order to assess its possible influence I anticipate the interpretation of $X(1785)^0$ as a composite structure where a D meson is strongly bound to other mesons. Binding of a meson to a composite structure is an exothermic reaction with a cross section inversely proportional to momentum. In the fireball near the production vertex, binding of D mesons is favored for those with low momentum, and it is the ones with high momentum that get away. A high-momentum cut that favors free D mesons is expected to eliminate most composites.

With these considerations in mind, evidence was sought in a review of $D^0 \to K^-\pi^+$ articles published through 1990 for which the D^0 did not derive from $\psi(3770) \to \bar{D}^0 D^0$ with beam-constrained energy, did not derive from cascade $D^{*+} \to D^0\pi^+$ with $D^0\pi^+$ mass constrained to the D^{*+} mass, and for which no high-momentum data cut was employed. Only exceptionally have such data been published. The TPS data in Figs. 4 and 12–14 qualify because the impact-parameter cut was relaxed for a demonstration of the effectiveness of the $\Delta z/\sigma_z$ cut. And fortunately HRS [13], CLEO [14], and ARGUS [15] have published such data for the $X^0 \to K^-\pi^+$ channel in e^+e^- experiments to illustrate the power of the high-momentum cut. Mass plots from their low-momentum cuts are shown in Figs. 16–18. Each shows evidence of a signal near 1785 MeV.

The curves in Figs. 4 and 16–18 have been fit with Gaussians near 1785 MeV. However the presumption of a signal can bias interpretation, and in establishing the significance of excess events at 1785 MeV it is preferable to test the data on the hypothesis that there is no signal. For this purpose unbiased curves were fit using the prescriptions given in the figure captions but omitting Gaussians near 1785 MeV. For these curves the excess events in the mass bins nearest 1785 MeV were compared

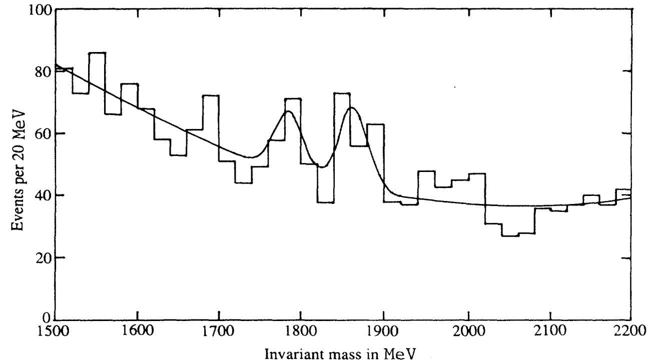

FIG. 16. Invariant masses for $K^-\pi^+$ events from e^+e^- annihilation. Data for $E/E_{max}<0.5$ from Figs. 2(a) and 2(b) of HRS [13]. Fit with a quadratic polynomial background plus Gaussians of equal width at the experimental D^0 mass and at 1785 MeV. A signal at 1785 MeV is suggested.

with the background events in the same bins, as described in the heading of Table III.

Because the TPS excursion in Fig. 4 was the first to be noticed and could in principle have arisen from a statistical fluctuation, no significance is attributed to it beyond the fact that it directs our attention to the possibility of a signal at 1785 MeV. Confirmation of this possiblity is sought in the other three experiments, and its significance is determined by the magnitudes of the other three excursions. As summarized in Table III these excursions are $+3.2\sigma$, $+3.1\sigma$, and $+1.1\sigma$. The joint probability that they could arise as independent statistical fluctuations is only about 10^{-5}. They are unlikely to have occurred by chance, and another interpretation of the TPS excursion must be sought. An unanticipated particle sharing the decay channel with D^0 appears to be most likely.

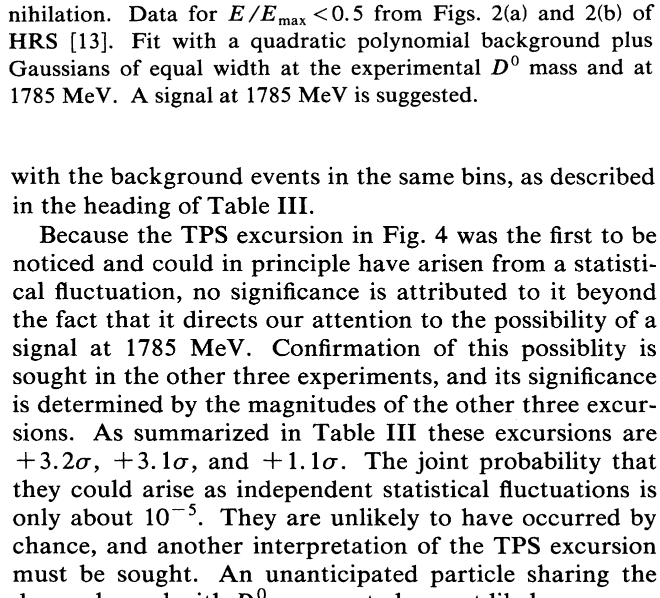

FIG. 17. Invariant masses for $K^-\pi^+$ events from e^+e^- annihilation. Data for $(E+P)/(E+P)_{max}<0.56$ from Fig. 1(a) of CLEO [14]. Fit with a cubic polynomial background plus Gaussians of equal width at the experimental D^0 mass and at 1785 MeV. The background, amounting to about 3000 events per mass bin in the neighborhood of 1785 MeV, has been subtracted. A signal at 1785 MeV is suggested.

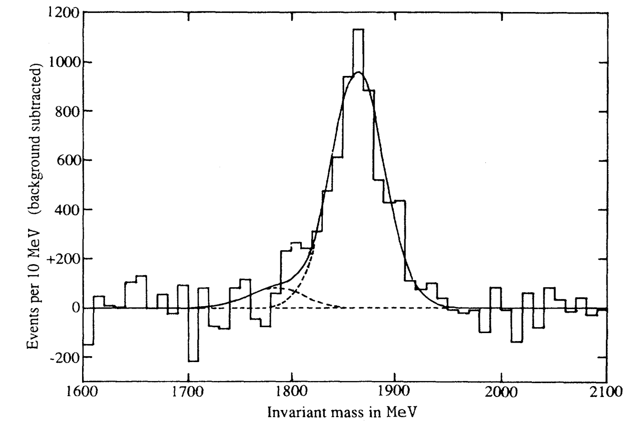

FIG. 18. Invariant masses for $K^-\pi^+$ events from e^+e^- annihilation. Data for $P/P_{max}<0.55$ from Figs. 1(a) and 1(b) of ARGUS [15]. Fit with a cubic polynomial background plus Gaussians of equal width at the experimental D^0 mass and at 1785 MeV. The background, amounting to about 9000 events per mass bin in the neighborhood of 1785 MeV, has been subtracted. There is a hint of a signal at 1785 MeV.

EVIDENCE FROM ASSOCIATED PRODUCTION

The mesons in Fig. 1 were produced in association with photons. ARGUS designed this experiment to provide evidence for the D_s^* meson in the decay channel $D_s^*\rightarrow D_s\gamma$ where subsequently the D_s decayed to $\phi\pi$. Invariant masses were determined for $\phi\pi\gamma$ combinations and for the embedded $\phi\pi$ combinations. A $\phi\pi$ invariant-mass plot was prepared for $\phi\pi\gamma$ combinations having invariant masses in the range $2080\le M(\phi\pi\gamma)\le 2170$ MeV spanning the D_s^* mass. The $\phi\pi$ mass plot showed a strong signal at the D_s mass in agreement with what was expected for D_s produced from D_s^* in association with γ. Mass plots for the sidebands $1990\le M(\phi\pi\gamma)\le 2080$ MeV and $2170\le M(\phi\pi\gamma)\le 2260$ MeV did not show $\phi\pi$ signals at the D_s mass, confirming that the D_s^* did not lie in the sideband regions.

In contrast with the situation where the full $\phi\pi$ signal for $M(\phi\pi)=1970$ MeV was found in a single $M(\phi\pi\gamma)$ mass range, $\phi\pi$ signals for $M(\phi\pi)=1800$ MeV are found in all three mass ranges. Their numbers are approximately 8 in the $\phi\pi\gamma$ mass range 1990–2080 MeV, 19 in the range 2080–2170 MeV, and 18 in the range 2170–2260 MeV. If these excursions represent decays of excited $X(1800)$ mesons there must be several different excited mesons $X_1^*(2035\pm45)$, $X_2^*(2125\pm45)$, and $X_3^*(2215\pm45)$, all decaying to $X\gamma$ with appropriate γ energies.

The Mark III experiment that provided data for Fig. 3 was designed to measure the mass of the D_s^* meson taking advantage of its production in associated with $\bar{D}_s$ in the reaction $e^+e^-\rightarrow D_s^*\bar{D}_s$ and of subsequent $\bar{D}_s$ decay to $\phi\pi$. The overall reaction is $e^+e^-\rightarrow\phi\pi R$ where R represents the recoil product or products. After the invariant mass and momentum are determined for a $\phi\pi$ combination, the recoiling invariant mass can be de-

TABLE III. Statistical significances of the excursions at 1785 MeV in Figs. 4 and 16–18. For these estimates the least-squares curves in the figures are not used. Instead least-squares curves are fit with a smooth background plus a Gaussian only for D^0, an approach that does not presume a signal at 1785 MeV. The significances of the excursions at 1785 MeV were estimated by selecting those mass bins whose centers fell within a half Gaussian width (HWHM) of 1785 MeV using the width determined for the D^0 peak, then considering the excess events in these bins over the background (including for Fig. 18 the overlapping D^0 events) as determined by the least-squares fits. Omitting the TPS data that initially directed attention to the possibility of a signal at 1785 MeV, the significances of the three other excursions are $+3.2\sigma$, $+3.1\sigma$, and $+1.1\sigma$. The joint probability that these three could result from independent statistical fluctuations is about 10^{-5}.

Figure	Mass range (MeV)	Ratio of excursion to background	Excursion in units of σ
4. TPS [4]	1770–1800	33/67	+4.0
16. HRS [13]	1760–1800	32/97	+3.2
17. CLEO [14]	1770–1800	293/9133	+3.1
18. ARGUS [15]	1750–1820	281/65 800	+1.1

duced. For $\phi\pi$ combinations with invariant masses near the D_s mass, a recoil mass plot showed a strong peak near 2110 MeV identified with D_s^*.

If the $\phi\pi$ signal at 1800 MeV in Fig. 3 is to be viewed as a new charmed meson X, it too must be produced in association with a particle of opposite charm in a primary reaction such as $e^+e^- \to X^*\bar{X}$.

Figure 19 shows the recoil mass plot for $\phi\pi$ combinations with invariant masses near 1800 MeV. A strong signal is observed near 2250 MeV, with a significance of 4.7σ. There are 10 events under the Gaussian at 1800 MeV in Fig. 3, equal to the 10 recoil events under the Gaussian near 2250 MeV in Fig. 19, supporting the view that the signals represent associated particle production and are not statistical fluctuations.

I interpret the signal in Fig. 19 as a recoil particle $X^*(2250)$ with the same charm and strangeness quantum numbers as $X(1800)$. It thus qualifies as a candidate for $X_3^*(2215\pm45)$ in the ARGUS experiment. The star on X^* indicates an excited state of X where in the composite meson model the constituents may be in an orbitally excited state, or where D may be replaced by D^* (or D_s by D_s^*, or K by K^*) as a constituent. In parallel with the radiative decays $D^* \to D\gamma$ and $D_s^* \to D_s\gamma$ the X^* can undergo radiative decay $X^* \to X\gamma$. Depending on the constituents of X there can be several excited states X_i^* that decay to $X\gamma_i$ with different photon energies.

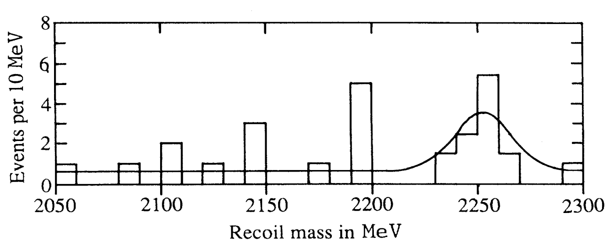

FIG. 19. Invariant masses for recoil events R in the reaction $e^+e^- \to \phi\pi R$. Data from Fig. 2 of Mark III [3], a scatterplot with $\phi\pi$ mass along the horizontal axis and recoil mass along the vertical axis. Events in the $\phi\pi$ mass range 1760–1840 MeV have been projected into 10-MeV bins along the recoil mass axis. Fit with a constant background plus a Gaussian near 2250 MeV having the same width as in Fig. 3. A recoil signal near 2250 MeV is suggested.

The cross section for associated production of particle pairs $e^+e^- \to A_1\bar{A}_2$ is greatest when the masses of the products lie within a pion mass of the e^+e^- energy, as in the Mark III reaction $e^+e^-(4140) \to D_s^*(2110)\bar{D}_s(1970)$ where the difference is 60 MeV, or in the reaction $e^+e^-(4140) \to X^*(2250)\bar{X}(1800)$ where the difference is 90 MeV. The cross section is expected to be significantly smaller when the products are light enough that a pion can accompany the production process. Mark III observed no recoil mass signal for $e^+e^-(4140) \to D_s(1970)\bar{D}_s(1970)$ where the mass difference is 200 MeV, presumably because most $D_s\bar{D}_s$ pairs were accompanied by a pion in the reaction $e^+e^- \to D_s\bar{D}_s\pi$ for which the recoil $D_s\pi$ invariant mass is spread out in the background. Similarly no recoil mass signal is expected in the Mark III data for $e^+e^- \to X^*\bar{X}$ for any X^* with mass less than about 2200 MeV below which $e^+e^- \to X^*\bar{X}\pi$ is expected to be dominant. The absence of recoil mass signals below 2200 MeV in Fig. 19 does not signify the absence of X^* particles with such masses.

INTERPRETATION

The excursions at 1800 MeV in $X^+ \to \phi\pi^+$ and at 1785 MeV in $X^0 \to K^-\pi^+$ present challenges of interpretation. Based on the cumulative evidence it is highly unlikely that they are the results of random fluctuations. Their narrow widths and their universal presence in a wide range of experiments with different production and detection methods makes it improbable that a coincidence of decay product misidentifications or other systematic errors could be responsible. The most likely alternative seems to be unanticipated particles sharing decay channels with D_s^+ and D^0. Both $X(1800)^+$ and $X(1785)^0$ have been observed at secondary vertices in charm lifetime experiments, suggesting that they are stable.

TABLE IV. Two- and three-component candidates for $X(1800)^+$ decaying to $\phi\pi^+$. [Note that insufficient energy is available for the bound $K\bar{K}$ pairs in $(D_sK\bar{K})^+$ and $(DK\bar{K})^+$ to annihilate.]

Composite	Charm	Strangeness	$\phi\pi$ channel Cabibbo suppressed?	Constraint
$(D_sK)^+$	1	2	Yes	
$(D_s\bar{K})^+$	1	0	Yes	
$(D_sK\bar{K})^+$	1	1	No	$J^P=0^{-}$ [a]
$(DKK)^+$	1	2	Yes	
$(DK\bar{K})^+$	1	0	Yes	

[a]Quantum numbers $J^P=0^-$ required to prohibit strong or single-photon electromagnetic decay of D_s^+. Two-photon decay $D_s^+\to(D_sK\bar{K})^+\gamma\gamma$ is allowed.

Hadron spectroscopy as currently understood has no room for additional stable mesons in this mass range, except possibly for strongly bound composites. This interpretation implies very strong binding indeed, with binding energies comparable to the masses of the lighter particles being bound. Yet is is difficult to imagine another interpretation.

I hypothesize that $X(1800)^+$ and $X(1785)^0$ are composites of D_s or D and other mesons. I assume that pions do not bind because of the large kinetic energy associated with confining them to so small a volume. Kaons are more likely to bind because they are more massive and the kinetic energy associated with binding is smaller. I tentatively assume that they do bind and consider the various composite structures that can result.

As matters of notation I consider that composites with positive charm are particles and those with negative charm are antiparticles, and I write composites in parentheses, for example, $(D^+\bar{K}^0)$, (D^+K^-), $(D^0\bar{K}^0)$, and (D^0K^-) as the four members of the $(D\bar{K})$ multiplet.

In considering candidate composites, I rule out those to which D_s^+, D^+, or D^0 could decay in strong or single-photon electromagnetic reactions, and also those for which the $X^+\to\phi\pi^+$ and $X^0\to K^-\pi^+$ decays would be doubly Cabibbo suppressed. The remaining two- and three-component candidates for $X(1800)^+$ are summarized in Table IV, and for $X(1785)^0$ they are summarized in Table V.

For reasons of symmetry and lack of Cabibbo suppression I lean toward the three-component mesons $(D_sK\bar{K})^+$ and $(DK\bar{K})^0$ as the most attractive candidates for $X(1800)^+$ and $X(1785)^0$, although a potential problem is raised by the requirement that branching fractions for the two-photon decays $D_s\to(D_sK\bar{K})\gamma\gamma$ and $D\to(DK\bar{K})\gamma\gamma$ be small compared with the dominant weak decays. Further information is required. Determination of the charge multiplicities in the $X(1800)$ and $X(1785)$ multiplets would help to clarify the situation.

The $(D_sK\bar{K})$ candidate for $X(1800)$ has a number of excited states. They are listed in order of descending mass in Table VI. If the $(D_sK^*\bar{K}^*)$ composite were to be identified with the 2250 MeV recoil particle in Fig. 19, its binding energy would be 1510 MeV, somewhat larger than the 1160-MeV binding energy of $(D_sK\bar{K})$ but perhaps appropriately so in view of its more massive constituents with their smaller kinetic energies. The binding energies of the other composites can be estimated as described in the table. The most massive composite might just be observable in $e^+e^-(4140)\to(\bar{D}_s^*\bar{K}^*K^*)(2330)$ $(D_sK\bar{K})(1800)$, depending on the accuracy of the mass extrapolation and on the availability of phase space so close to the limit. The Mark III data did not extend to recoil masses greater than 2300 MeV, so this question remains open. Three excited composites are candidates for X_1^*, X_2^*, and X_3^* in the ARGUS experiment, as indicated in the table. Although highly speculative, the analysis in Table VI is intended to be illustrative of how the excited states of composites may be able to account for the associated production of photons and recoil particles in the ARGUS and Mark III experiments.

The existence of charm mesons $X(1800)^+$ and $X(1785)^0$ implies their potential observability in a wide range of experiments. Where these mesons are expected but not yet reported, there must be a corresponding avail-

TABLE V. Two- and three-component candidates for $X(1785)^0$ decaying to $(K\pi)^0$. [Note that insufficient energy is available for the bound $K\bar{K}$ pair in $(DK\bar{K})^0$ to annihilate.]

Composite	Charm	Strangeness	$K\pi$ channel Cabibbo suppressed?	Constraint
$(D_s\bar{K})^0$	1	0	No	
$(DKK)^0$	1	2	No	
$(DK\bar{K})^0$	1	0	No	$J=0$ [a]

[a]Quantum number $J=0$ required to prohibit single-photon electromagnetic decay of D. Two-photon decay $D\to(DK\bar{K})\gamma\gamma$ is allowed.

TABLE VI. Excited states of the $(D_sK\bar{K})$ candidate for $X(1800)$. Identification of $(D_sK^*\bar{K}^*)$ with the 2250 MeV recoil particle in Fig. 19 is highly speculative, intended to be illustrative of how the excited states of composites may be able to account for the associated producton of photons and recoil particles in the ARGUS and Mark III experiments. Mass and energy are in MeV.

Composite	Constituent mass	Binding energy	Bound mass	Possible ARGUS X_i^* decaying to $X\gamma$
$(D_s^*K^*\bar{K}^*)$	3900	1570 [a]	2330	
$(D_sK^*\bar{K}^*)$	3760	1510	2250	$X_3^*(2215\pm45)$
$(D_s^*K^*\bar{K}),(D_s^*K\bar{K}^*)$	3500	1395 [a]	2105	$X_2^*(2125\pm45)$
$(D_sK^*\bar{K}),(D_sK\bar{K}^*)$	3360	1335 [a]	2025	$X_1^*(2035\pm45)$
$(D_s^*K\bar{K})$	3100	1220 [a]	1880	
$(D_sK\bar{K})$	2960	1160	1800	

[a]Fit to the linear relationship (binding energy) $= -91+0.4375$ (constituent mass) passing through 1510 for $(D_sK^*\bar{K}^*)$ and 1160 for $(D_sK\bar{K})$, rounded to the nearest 5 MeV.

able residuum of unidentified charm events.

Although no $X(1800)$ or $X(1785)$ signals have been seen in $\psi(3770)$ decay they are expected, and a proportion of as yet unidentified decays must remain available for them. For some time it was thought that $\psi(3770)$ decayed nearly exclusively to $D\bar{D}$ but recent measurements have suggested that production of $D\bar{D}$ accounts for only about 75% of the decays [16] leaving about 25% available for $X\bar{X}$ and $X^*\bar{X}$. The original thought that $\psi(3770)$ decays almost exclusively to charm remains valid.

The $X(1800)$ and $X(1785)$ mesons should also be observable in the decay $\psi(3685)\rightarrow X\bar{X}$. There have been no searches for charm from $\psi(3685)$ decay but there are about 15% of decays known to be hadronic but as yet unidentified. They remain available for $X\bar{X}$.

In emulsion and bubble-chamber experiments charm particles are isolated by requiring a secondary vertex clearly separated from the primary vertex, with decay products clearly distinct from those associated with strange-particle decays. The $X(1800)$ and $X(1785)$ mesons would survive these data cuts and should be observable. Because of uncertainties in particle identification there have often been ambiguities of identification among the established charm particles D, Λ_c, and D_s. As experimental techniques have improved the proportion of ambiguities has diminished but a residuum of unidentifiable charm events remains. A recent paper by the LEBC-EHS Collaboration [17] summarizes results from 2.22×10^6 tagged bubble-chamber pictures. The data cuts isolating charm events resulted in a sample of 320 events containing 557 charm decays with an estimated noncharm background less than two decays. Of the 557 charm decays 482 can be interpreted as D^+, Λ_c^+, D_s^+, or D^0, 425 with a clear topology and 57 with an ambiguous one. The remaining 75 decays are most probably charm (they are paired to a charm decay) but they cannot be fully ascertained as such. These decays are available for interpretation as $X(1800)$ and $X(1785)$ mesons.

SUMMARY

Signals at 1800 MeV and at 1785 MeV in invariant-mass plots from a wide range of sources have been interpreted as composite charm mesons $X(1800)^+$ and $X(1785)^0$. It is improbable that a coincidence of statistical fluctuations could be responsible for these signals and unlikely that a coincidence of decay product misidentifications or other systematic errors could be responsible. The composite-meson interpretation appears most probable. In every instance where $X(1800)^+$ or $X(1785)^0$ mesons are expected there is evidence for them or evidence for their potential presence as unidentified charm. Confirmation of these hadrons would establish a new and fruitful field of hadron spectroscopy.

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