Production of ϕ and $F(1970) \to \phi\pi$ in e^+e^- Annihilation at 29 GeV

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Data from the high-resolution spectrometer at PEP have been used to study the inclusive production of ϕ mesons and $F^{\pm}$ mesons decaying into $\phi\pi^{\pm}$. Fragmentation functions and cross sections are presented and compared to existing data. The total ϕ cross section at 29 GeV is 40 ± 6 pb. The observed F signal in the region $z > 0.4$, given the assumption that $R(F)/[R(F)+R(D)] = 0.15$, corresponds to an $F \to \phi\pi$ branching ratio of $(3.3 \pm 1.1)\%$. The measured F mass is $1963 \pm 3 \pm 3$ MeV/c^2.

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This Letter reports results on ϕ meson production and the observation of a narrow $\phi\pi$ state at 1970 MeV/c^2 in e^+e^- annihilation at 29 GeV. The narrow state at 1970 MeV/c^2 is consistent with the lowest-lying charm-strange meson F observed by Chen *et al.*[1] and confirmed by Darden *et al.*[2] both at lower center-of-mass energies. The F has also been reported by Althoff *et al.*[3] at PETRA.

The hadronic events used in the analysis come from an integrated luminosity of 176 ± 6 pb^{-1} obtained with the high-resolution spectrometer at the Stanford Linear Accelerator Center storage ring PEP. The detector, which utilizes a solenoidal magnetic field of 1.62 T, is described elsewhere.[4] Hadronic events were selected by demanding more than five vertex-fitted tracks and that the visible energy be greater than 13 GeV.

To search for ϕ production in these events all possible K^+K^- mass combinations were formed. The pion background in the kaon sample was reduced by rejection of all track candidates with momenta less than 1.5 GeV/c and flight times inconsistent with a kaon interpretation. The difference in the flight times of π and K mesons at 1.5 GeV/c is equal to our time resolution of $\sigma = 360$ psec. In addition, the absence of a Čerenkov signal was required for kaon candidates with momenta below the kaon threshold.[5]

The K^+K^- invariant-mass distribution is shown in Fig. 1(a) for $z_{KK} > 0.1$ and in Fig. 1(b) for $z_{KK} > 0.4$, where $z_{KK} \equiv 2E_{KK}/\sqrt{s}$. A clear signal corresponding to ϕ production is observed with an excellent signal-to-noise ratio in the higher momentum selection. The ϕ signal was determined by a fit of the mass spectra with a smooth background and a resonance contribution described by a convolution of a p-wave Breit-Wigner curve with full width at half maximum (FWHM) of

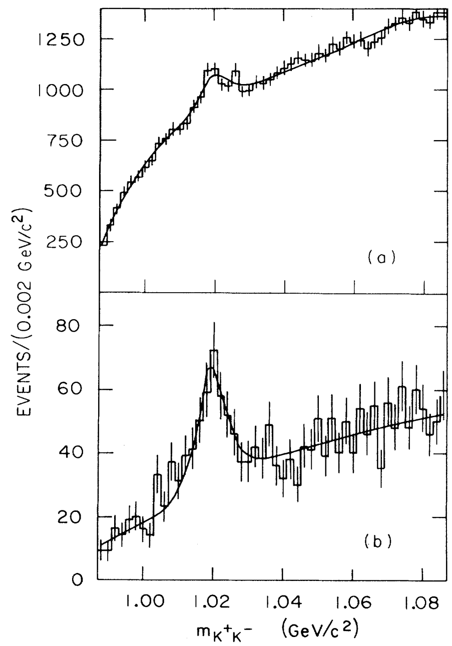

FIG. 1. The K^+K^- invariant-mass spectrum for (a) $z(K^+K^-) > 0.1$ and (b) $z(K^+K^-) > 0.4$.

4.1 MeV/c^2 and a Gaussian curve representing the spectrometer resolution. The latter, as determined by a Monte Carlo calculation, averages 7 MeV/c^2 FWHM over the ϕ momentum range. The resulting composite FWHM is 9.5 ± 2.0 MeV/c^2. The ϕ signal displayed in Fig. 1(a) contains 948 ± 102 events and in Fig. 1(b) 217 ± 25 events.

The differential cross section was determined from a series of fits to the K^+K^- mass spectra for several intervals of z. In these fits the ϕ mass was fixed at 1019.6 MeV/c^2 and the width was set as described above. The detector acceptance was determined by a similar series of fits to ϕ events generated by a Monte Carlo simulation. The overall detection efficiency (including the $\phi \to K^+K^-$ branching ratio of 0.49) ranges from 10% to 20% and increases smoothly with momentum. The number of ϕ events determined from these fits, after correction for the acceptance, are plotted as $(s/\beta)d\sigma/dz$ in Fig. 2 and given in Table I. No z correction has been made to compensate for the effects of initial-state radiation. Our precise data are in good agreement in magnitude and shape with the ϕ fragmentation in the Lund Monte Carlo simulation[6] and with results from Aihara *et al.*[7]

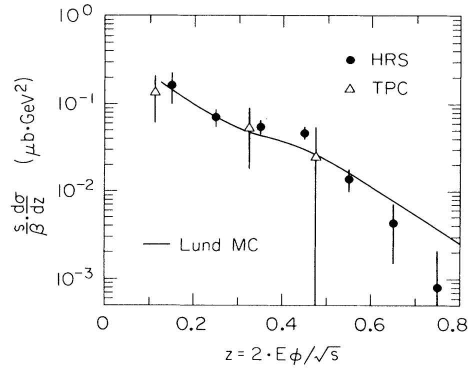

FIG. 2. The ϕ fragmentation function as measured by the present experiment (HRS) and Aihara *et al.* (Ref. 7) (TPC).

The inclusive ϕ production cross section measured for $z > 0.1$ is 39 ± 6 pb. A linear extrapolation to the threshold of $z_{\rm th} = 0.07$ yields a total ϕ production cross section of $\sigma(\phi) = 40 \pm 6$ pb. Dividing by the μ-pair cross section for $\sqrt{s} = 27.3$ GeV to correct for initial-state radiation gives $R(\phi) = 0.34 \pm 0.05$.

To search for the decay mode $F \to \phi\pi$, each K^+K^- combination in the ϕ mass band (1019.6 ± 10) MeV/c^2 was combined with each other track in the event taken as a pion. An enhancement is observed in the resulting $\phi\pi$ effective-mass spectrum shown in the upper histogram of Fig. 3(a) for $0.2 < z(\phi\pi) < 0.4$ and in the upper histogram of Fig. 3(b) for

TABLE I. ϕ and F fragmentation functions.

z range	ϕ $(s/\beta)d\sigma/dz$ (nb GeV^2)	F $(s/\beta)(d\sigma/dz)B(F \to \phi\pi)$ (nb GeV^2) No θ cut	With θ cut
0.1–0.2	164 ± 64		
0.2–0.3	71 ± 16	19.7 ± 7.0	10.3 ± 5.3
0.3–0.4	55 ± 10	3.1 ± 3.4	3.7 ± 3.4
0.4–0.5	47 ± 7	4.2 ± 1.9	7.2 ± 2.5
0.5–0.6	14 ± 4	2.1 ± 1.5	2.1 ± 1.5
0.6–0.7	4.3 ± 2.8	0.6 ± 0.7	2.4 ± 1.0
0.7–0.8	0.8 ± 1.3	1.2 ± 0.7	1.2 ± 1.0

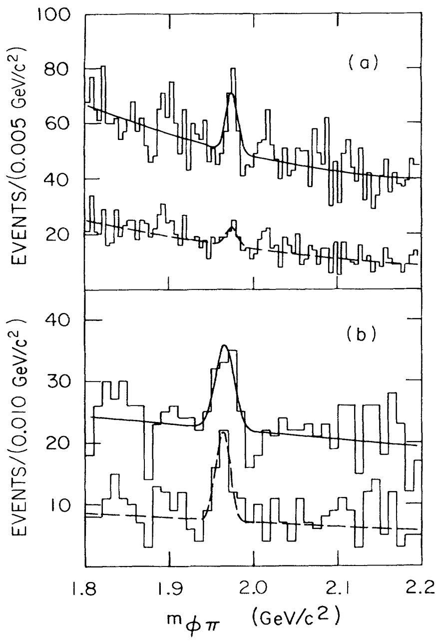

FIG. 3. The $\phi\pi$ invariant-mass spectrum for events with (a) $0.2 < z(\phi\pi) < 0.4$ and (b) $z(\phi\pi) > 0.4$. The lower histograms are selected in particular ranges of the decay angles as discussed in the text.

$z(\phi\pi) > 0.4$, where $z(\phi\pi) \equiv 2E(\phi\pi)/\sqrt{s}$. The separation of the data into two regions of z is motivated by the different mechanisms expected for F production. The region $z > 0.4$ is dominated by direct charm whereas the data with $0.2 < z < 0.4$ contain the majority of the events from B decay. The fit shown by the full line in Fig. 3(b) yields 37 ± 13 events centered at a mass of 1967 ± 5 MeV/c^2 and with a width of 25 ± 6 MeV/c^2. The observed width is consistent with the calculated spectrometer resolution of 19 ± 1 MeV/c^2. The upper histogram of Fig. 3(a) was fitted with a Monte Carlo–calculated resolution of 15 MeV and yielded a peak of 70 ± 18 events centered at a mass of 1975 ± 2 MeV/c^2. When the width was permitted to vary in the fit, a value of 9 ± 2 MeV/c^2 was obtained.

The enhancement is not seen in the three-body invariant-mass plot using K^+K^- combinations outside of the ϕ mass band. Furthermore, the tracks in the peak region, when combined under any alternative identity hypothesis (p, K, or π), show no clustering at any particular mass value. This rules out the possibility of another resonance, known or unknown, strongly reflecting into the observed peak region of the $\phi\pi$ spectrum.

The enhancements in both z regions were tested for consistency with a 0^- spin assignment of the F. The events were divided into two regions, $|\cos(\theta)| < 0.5$ and $|\cos(\theta)| > 0.5$, where θ is the angle between the F (ϕ) direction in the laboratory (F) system and the ϕ (K) direction in the F (ϕ) center of mass. Equal populations are expected for the $F(0^-) \to \phi\pi$ decay and a $\cos^2(\theta)$ distribution in the helicity frame of the ϕ for the subsequent ϕ decay ($1^- \to 0^-0^-$). Table II contains the event counts, errors, and probabilities that the observed events result from the decay of a 0^- particle into $\phi\pi$.

TABLE II. Events, errors, and probabilities that the observed events result from the decay of a 0^- particle into $\phi\pi$.

z range	Event count $\cos\theta < 0.5$	Event count $\cos\theta > 0.5$	Probability (%)
	F meson		
$0.2 < z < 0.4$	10 ± 10	60 ± 15	0.5
$z > 0.4$	15 ± 8	22 ± 10	58
	ϕ meson		
$0.2 < z < 0.4$	32 ± 12	38 ± 13	1
$z > 0.4$	0 ± 7	37 ± 11	48

Above $z = 0.4$ the peak is entirely consistent with the 0^- interpretation. If the data are restricted to the decay region $|\cos(\theta)| > 0.5$ for the ϕ decay and $|\cos(\theta)| < 0.7$ for the $\phi\pi$ decay, as a means of enhancement of the 0^- signal relative to background, the histogram in the lower part of Fig. 3(b) is obtained. The fit shown by the dashed curve gives a signal of 30 ± 8 events. This yields our best estimate of the F mass of $1963 \pm 3 \pm 3$ MeV/c^2.

Below $z = 0.4$ the probability that the peak is due to a 0^- F meson decay is $\leq 1\%$. By restriction of the decay angular ranges as described in the previous paragraph, the peak at 1975 MeV/c^2 is reduced in proportion to the background, as seen in the lower histogram of Fig. 3(a). The fit shown by the dashed curve gives a signal of 23 ± 11 events.

The z dependence of the F production was determined by a series of fits to the $\phi\pi$ mass spectrum for successively larger z selections by use of widths determined by the Monte Carlo calculation. The data were corrected for acceptance and the resulting fragmentation functions $D(z) \equiv (s/\beta)\, d\sigma/dz$ are listed in Table I both with and without the decay-angle cuts. The data from the restricted decay-angular regions, which enhance the 0^- component and improve the signal-to-noise ratio, are shown in Fig. 4. The solid curve is a fit by the Peterson fragmentation function[8] for our D^* mesons[9] in the region $z > 0.4$, normalized to our $\phi\pi$ data in the same region.

Suzuki[10] has estimated the contribution to F production from B meson decay to be $(21 \pm 2)\%$ of the b quark production rate. This estimate includes a contribution from the $c\bar{s}$ decay of the W. The dashed curve in Fig. 4 is the sum of this prediction (with use of our

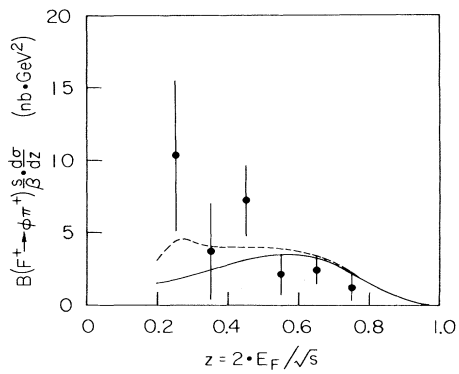

FIG. 4. The F fragmentation function. The solid curve is the Peterson-form fit to our D^* fragmentation for $z(D^*) > 0.4$. The dashed curve is the sum of the solid curve and the estimated contribution from B decay.

measurement of the $F \to \phi\pi$ branching ratio) and the solid curve of Fig. 4. The data point calculated without an angle cut for $0.2 < z < 0.3$ of 19.7 ± 7.0 nb·GeV^2 (Table I) is 2 standard deviations above the dashed curve. As previously discussed the signal in this region is not consistent with a 0^- F meson interpretation.

The product of the total cross section and branching ratio for $z > 0.4$ is $\sigma(F^+ + F^-)B(F \to \phi\pi) = 1.57 \pm 0.40$ pb, which corresponds to $R(F^+ + F^-)B(F \to \phi\pi) = 0.0135 \pm 0.0034$. Comparing this result to our measurement of $R(D + \bar{D}) = 2.2 \pm 0.5$ in the same z region yields $R(F)B(F \to \phi\pi)/R(D) = 0.0059 \pm 0.0020$. This leads to a branching ratio $B(F \to \phi\pi) = (3.3 \pm 1.1)\%$ (statistical errors only), under the assumption that $R(F)/[R(D) + R(F)] = 0.15$ to be consistent with the assumption of Chen *et al.* for comparison. This result is consistent with the 4.4% reported by Chen *et al.* The value of Althoff *et al.* for this ratio under similar assumptions is $(13 \pm 5)\%$.

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