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Observation of $\phi K\pi$ decay of the $K^{*0}(2060)$

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We have studied inclusive $pN\rightarrow K^+K^-K^+K^-X$ final states at 400 GeV/c and present here evidence for $K^{*0}(2060)\rightarrow\phi K^{\pm}\pi^{\mp}$ and $\phi K^{*0}(890)$.

Excitations of the neutral kaon $K(498)$, presumed to be d and $\bar{s}$ quarks in the $^1S_0$ ground state, have been observed: $K^*(890)$ ($^3S_1$), $K^*(1430)$ ($^3P_2$), $K^*(1780)$ ($^3D_3$), and $K^*(2060)$ ($^3F_4$) (Ref. 1). Since our trigger gives greatest sensitivity to $\phi K(n\pi)$ decay modes of the K^*, and since $K^*(1780)$ decaying to $\phi K(n\pi)$ has its peak in the steeply rising portion of the $(2+n)$-body mass spectrum, we analyze the $\phi K(n\pi)$ decay modes of the $K^*(2060)$. Those modes accessible in our experiment, which lack neutral particle identification, are listed in Table I. The $\phi K^{\pm}\pi^{\pm}$ and $\phi K^{*0}(890)$ final states show strongest evidence for $K^*(2060)$. We compare the results with other experiments, especially those that observe $K^*(2060)$ decays to $\rho K\pi$ and $\omega K\pi$.

Experiment E623 used the Fermilab multiparticle spectrometer (FMPS) in the 400-GeV/c M6W beam line to study proton-nuclei interactions with ϕ mesons in the final state.[2] A fast trigger processor[3] identified events with at least two K^+K^- pairs whose effective masses in the magnet bend plane were consistent with that of the ϕ. An atmospheric, multicell, nitrogen Cherenkov counter with momentum thresholds of 5.7 (π), 20.2 (K), and 38.3 (p) GeV/c provided track-by-track particle identification for this trigger.

Pattern recognition, a global three-dimensional six-parameter track fit, and particle identification reduced the 3.7×10^6 triggers to 1.8×10^6 events each having ≥ 3 tracks with ≥ 1 K^+ and ≥ 1 K^-. Tracks without Cherenkov light with $5.8\leq P\leq 23.0$ GeV/c were defined as kaons and with $23.0\leq P\leq 38.3$ GeV/c were defined as protons, while all particles with associated light were assumed to be pions. Events with ≥ 2 K^+ and ≥ 2 K^- (the 144 471-event four-K sample) included 32 044 events with ≥ 1 K^+K^- mass combination within ± 6 MeV/c^2 of the nominal ϕ mass.[4] Of these, $\sim$80% (25 482 events) had ≥ 1 additional $K^+\pi^{\mp}$. Our fitted ϕ mass (1.0199±0.0003

TABLE I. Possible $\phi K(n\pi)$ final states of $K^{*0}(2060)$.

Reaction	Q value (MeV)	Monte Carlo acceptance fraction	Fitted events
$K^{*0}(2060)\rightarrow\phi K^{\pm}\pi^{\mp}$	407	0.0040	431±116
$K^{*0}(2060)\rightarrow\phi K^{*0}(890)$	148	0.0034	172±78
$K^{*\pm}(2060)\rightarrow\phi K^{\pm}$	547	0.0044	35±58
$K^{*\pm}(2060)\rightarrow\phi K^{\pm}\pi^{\pm}\pi^{\mp}$	268	0.0010	8±3
		0.0037	107±128[a]

[a]Including tracks with $P\leq 5.8$ GeV/c as pions.

GeV/c^2) and resolution, described elsewhere,[4] are used to establish the mass scale. A 4% systematic momentum error would have resulted in a ϕ mass 5σ from its nominal value, with a corresponding $\phi K\pi$ mass shift of 17 MeV/c^2 at a $\phi K\pi$ mass of 2060 MeV/c^2. Thus we are confident of our mass calibrations.

In our fits we parametrize the background by $N(M-M_0)^{\alpha}e^{-\beta(M-M_0)}$, where the threshold mass (M_0), the normalization (N), α, and β were varied. This form, one of several tried, fits the highly trigger biased background spectrum over the broadest range. The resonance contribution was insensitive, within the uncertainties of the fit, to the particular background chosen. The resonance is a Breit-Wigner form convoluted with the Gaussian instrumental resolution [$\sigma=10$ MeV/c^2 for $K^*(2060)$] determined by Monte Carlo methods. The solid curve on each histogram is the overall fit, whereas the dashed curve is the fitted background when it is distinguishable from the overall fit.

Since the $K^*(2060)$ is an established resonance, we searched for enhancements in the $\phi K(n\pi)$ mass spectrum in the vicinity of this mass. Furthermore, we examined the $K\pi$ mass spectrum for $K^*(890)$ submass of the $K^*(2060)$. The enhancements we observed in the $\phi K\pi$ and $K\pi$ mass spectrum near 2060 and 890 cannot be ascribed to pathological behavior of our trigger acceptance nor to incorrect particle-mass identification. This has been verified by extensive Monte Carlo and mass substitution studies, i.e., $K\to p$ or π and $\pi\to K$ or p. Hence we have confidence in the integrity of the data that is presented here.

The $\phi K^{\pm}\pi^{\mp}$ mass spectrum is seen in Fig. 1. When tracks below pion threshold are included as pions, a (502 ± 188)-event enhancement whose mass and width are 2048 ± 10 and 60 ± 59 MeV/c^2 is extracted (χ^2/DF=36/30). To ensure that pions are positively identified, tracks with momentum below 5.8 GeV/c were excluded, a (431 ± 116)-event enhancement with mass and width 2079 ± 7 and 61 ± 58 MeV/c^2 (χ^2/DF=16/23) remained. These masses and widths are consistent with previous $K^*(2060)$ measurements.[5-8]

To confirm the consistency of these results we fit the data of Fig. 1(b) to the background form, i.e., without resonance contributions, by excluding three then five 20-MeV/c^2 bins centered on the resonance. The event excess above the fitted background is 222 or 266, respectively. Using the fitted Γ, this implies 419 or 426 resonance events, respectively. This is to be compared with the 431-event enhancement extracted from the overall fit. When this process is repeated for five other "reasonable" background forms, the range of event excess is 217—229 or 255—281, respectively. This demonstrates the insensitivity of our results to the background form. If the full spectrum is fitted to background only, then χ^2/DF=31.3/29. The three bins centered on the resonance contribute a χ^2 of 11.8, implying a probability of $\sim1.5\%$ for the hypothesis without resonance.

In what follows we require positively identified pions ($P\geq5.8$ GeV/c). The background is constructed of K^+K^- pairs with $1008\leq M(K^+K^-)<1014$ and $1026\leq M(K^+K^-)<1032$ MeV/c^2, the ϕ sideband ("ϕ"). These "ϕ"$K^{\pm}\pi^{\mp}$ fits, with fixed resonance mass (2079 MeV/c^2) and width (61 MeV/c^2), give 81 ± 104 $K^*(2060)$ events (χ^2/DF=36/26), implying that the signal is entirely in the $\phi K^{\pm}\pi^{\mp}$ submass of $K^+K^-K^{\pm}\pi^{\mp}$. Our measured $\phi K^+\pi^+$ and $\phi K^-\pi^-$ distributions are structureless, consistent with an isospin-$\frac{1}{2}$ assignment for this resonance.

The background-subtracted, acceptance-corrected transverse-momentum distribution fitted to $\exp(-bP_T{}^2)$ gives b of 2.3 ± 0.7 (GeV/c)$^{-2}$, consistent with other K^* productions.[9] The longitudinal-momentum-fraction distribution (X_F) could not be determined since our trigger acceptance limited the kaon momentum and hence our sensitivity to $|X_F|\leq0.1$.

To investigate the two-body decay mode $K^{*0}(2060)\to\phi K^{*0}(890)\to\phi K^{\pm}\pi^{\mp}$ we fit the $K^{\pm}\pi^{\mp}$ mass spectrum, seen in Fig. 2, by fixing the resonance mass and width (892 and 52 MeV/c^2), and obtain 465 ± 137 $K^*(890)$ events (χ^2/DF=72/50). We then fit the $\phi K^{\pm}\pi^{\mp}$ mass, seen in Fig. 3, for $K^{\pm}\pi^{\mp}$ mass combinations within ±40 MeV/c^2 of the $K^{*0}(890)$, with fixed mass and width (2079 and 61 MeV/c^2). This fit when corrected for background and $K^*(890)$ combinations excluded by the cut gives 172 ± 78 $\phi K^{*0}(890)\to\phi K^{\pm}\pi^{\mp}$ combinations. Given our trigger requirements, $\sim40\%$ of the $K^{*0}(890)$-event sample is a decay product of $K^{*0}(2060)$.

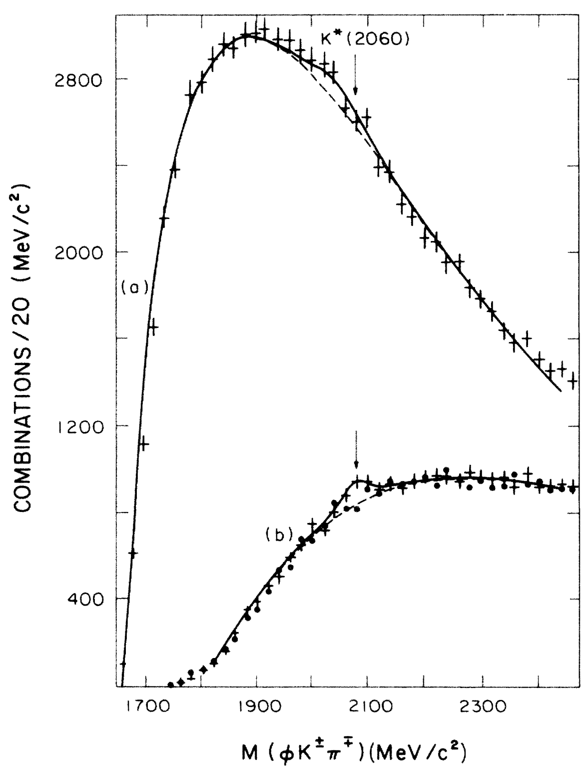

FIG. 1. The $\phi K^{\pm}\pi^{\mp}$ mass spectra, crosses, fitted to background and $K^*(2060)$ for (a) all tracks; (b) tracks with $P\leq5.8$ GeV/c excluded. The dotted histogram is the "ϕ"$K^{\pm}\pi^{\mp}$ data normalized to the background fit of the crossed histogram. Error bars on the dots are comparable to the error bars on the crosses but have been omitted for clarity.

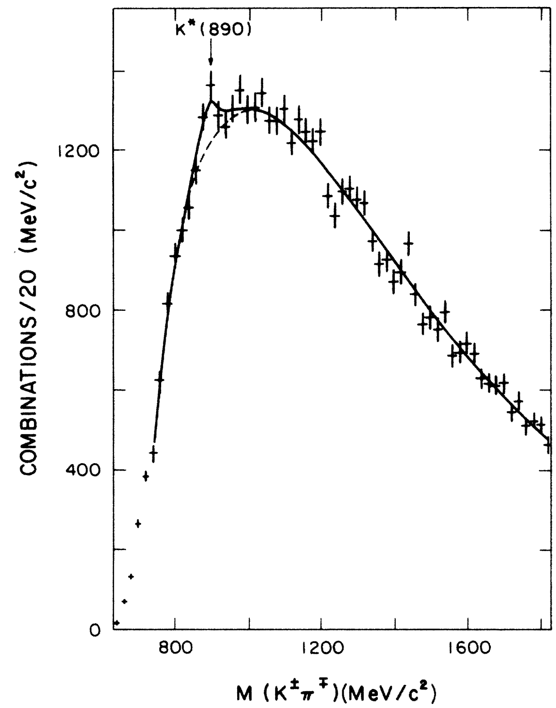

FIG. 2. The $K^{\pm}\pi^{\mp}$ mass spectrum fitted to background and $K^*(890)$. Tracks having $P \leq 5.8$ GeV/c are excluded.

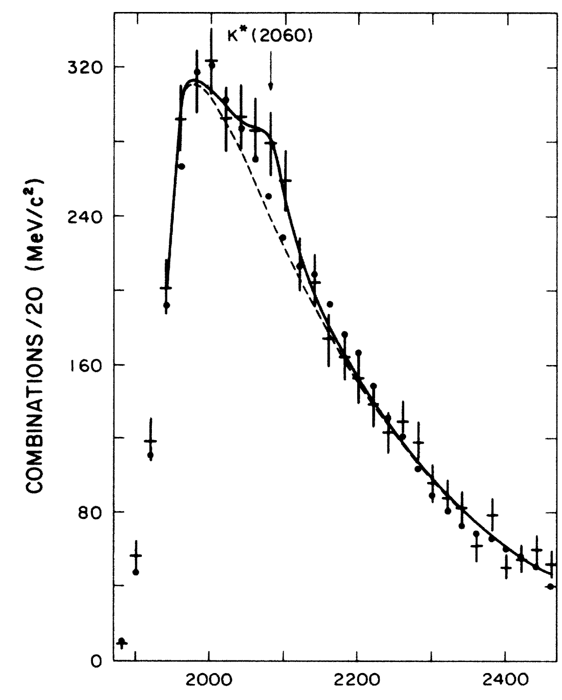

FIG. 3. The $\phi K^{\pm}\pi^{\mp}$ mass spectra for $K^{\pm}\pi^{\mp}$ in the $K^*(890)$, crosses, fitted to background and $K^*(2060)$. The dotted histogram is the "ϕ"$K^*(890)$ data normalized to the background fit of the crossed histogram. Tracks having $P \leq 5.8$ GeV/c are excluded. Error bars on the dots are comparable to the error bars on the crosses but have been omitted for clarity.

Centrally produced resonances should be charge symmetric.[10] From the fits to the $\phi K^{\pm}\pi^{\mp}$ mass spectra seen in Fig. 4,

$$N(K^{*0}(2060)\to\phi K^{+}\pi^{-})/N(\bar{K}^{*0}(2060)\to\phi K^{-}\pi^{+}) = 0.8\pm0.4\ ,$$

consistent with $\bar{s}d$ and $s\bar{d}$ production rates being comparable and in agreement with $N(K^{+})/N(K^{-})$ data.[11] We see no evidence above the one σ level for $K^*(2060)$ being pair produced with any known $\bar{K}^*$ resonance.

We evaluate the $K^{*0}(2060)$ cross section (σ) using a model to obtain the branching ratio (B) from our measured $(d\sigma/dX_F\,|\,_{X_F=0})B$. Our cross-section normalization, details to be found elsewhere,[2] includes geometrical acceptance, Cherenkov, trigger, and reconstruction efficiencies, and corrections for kaon decays before the Cherenkov counter (0.621), the $\phi\to K^{+}K^{-}$ branching fraction (0.49), and the $K^{*0}(2060)\to\phi K\pi$ relative branching fraction to charged particles (0.667).

To study the acceptance fraction we generated $K^*(2060)$ events with a differential cross section of $(1-|X_F|)^{2.8}\exp(-2.5P_T^{2})$ (Ref. 9) and propagated them through the apparatus, trigger processor, and analysis software. The acceptance fraction is insensitive to the particular choice of transverse-momentum distribution. However, it is rather sensitive to the model of the fourth (bachelor) kaon required by the trigger. The results reported in Table I are based on the Bourquin-Gaillard model[12] with local quantum-number conservation, in this

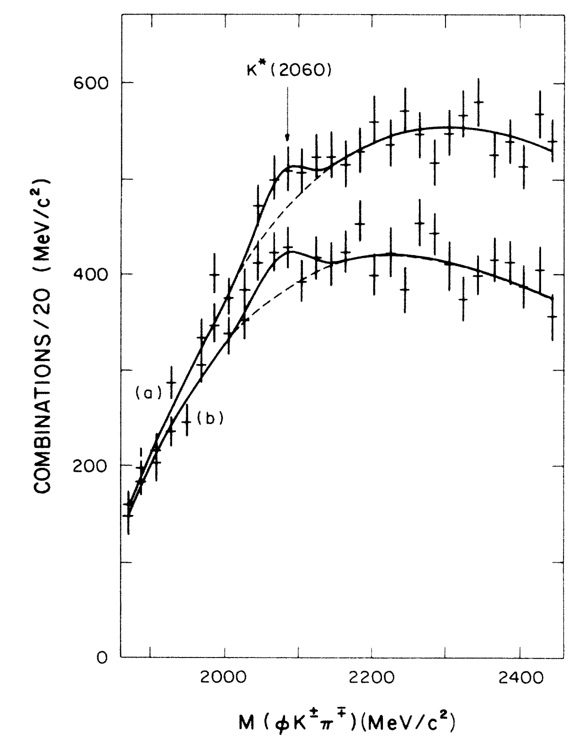

FIG. 4. The mass spectra fitted to background and $K^*(2060)$ for (a) $\phi K^{+}\pi^{-}$; and (b) $\phi K^{-}\pi^{+}$. Tracks having $P \leq 5.8$ GeV/c are excluded.

case strangeness. Hence, the bachelor kaon is produced close in phase space to the $K^{*0}(2060)\to\phi K^{\pm}\pi^{\mp}$ which allows low-mass $K^{\pm}K^{\mp}$ (bachelor) combinations to provide the second trigger ϕ.

The corrected $(d\sigma/dX_F\,|_{X_F=0})B(\phi K\pi)$ is 1.18 ± 0.32 μb. Extrapolating to the total cross section by $2(d\sigma/dX_F\,|_{X_F=0})/(n+1)$, using $n=2.8$ from $K^{*0}(890)$ production,[9] yields $\sigma B(\phi K\pi)=0.64\pm0.17$ μb. The Bourquin-Gaillard model[12] estimates the total inclusive cross section

$$\sigma\ (\mu\text{b})=4\times10^9 {y_{\max}}^2\exp(-5.13/{y_{\max}}^{0.38})\times M'(M'+2)^{-12.3}\ .$$

M' is the mass of the simplest composite particle consistent with the production of resonance mass M and local conservation of quantum numbers. Here M is 2060 MeV/c^2, M' is 2060+490 MeV/c^2, and $y_{\max}$ is the maximum center-of-mass rapidity for M'. In this model $\sigma(pp\to K^{*0}(2060)\bar{K}X+\bar{K}^{*0}(2060)KX)$ is 22 μb. Using this estimated σ, the B for $K^{*0}(2060)$ to $\phi K\pi$ is 0.028 and to $\phi K^{*0}(890)$ is 0.014. The errors, which depend on the accuracy of the model, are estimated to be $\sim50\%$ of these values.[13]

Using this model to infer the ϕK^* branching ratio, and using the measured[5] branching ratio to $K\pi$, $\frac{3}{2}(0.07\pm0.01)$, we obtain

$$\Gamma(\phi K^{*0}(890))/\Gamma((K\pi)^0)=0.13\pm0.07\ .$$

This result is consistent[6] with

$$\Gamma(\rho^0K^{*0}(890))/\Gamma((K\pi)^0)=0.06\pm0.03\ ,$$

implying comparable branching fractions for neutral isovector or isoscalar members of the same nonet. Our derived ratio, $\Gamma(\phi K\pi)/\Gamma((K\pi)^0)=0.27\pm0.14$, when compared[7] with $\Gamma(\omega\bar{K}^0\pi^-)/\Gamma(\bar{K}^0\pi^-)=0.50\pm0.30$ and $\Gamma(\rho^0\bar{K}^0\pi^-)/\Gamma(\bar{K}^0\pi^-)=0.58\pm0.32$, agrees within the measurement uncertainties.

The decays of $K^*(2060)$ to $K^{\pm}\pi^{\mp}$, $\phi K^{\pm}\pi^{\pm}\pi^{\mp}$, and $\phi K^{\pm}$ are not seen in our data. Fits with a resonance contribution, Table I, give nearly identical χ^2 to ones without a resonance contribution. The first decay mode is suppressed because the four-kaon trigger requirement excludes these events. The second decay mode is possibly suppressed because of small B's and/or large combinatorial backgrounds when multiple pions are included. No other experiment has reported $K^*(2060)$ decay modes comparable to $\phi K\pi\pi$, e.g., $\rho K\pi\pi$ and $\omega K\pi\pi$. In order to make further comparisons with existing data, we assume equal cross sections for $K^{*0}(2060)K^-X$ and $K^{*+}(2060)K^-X$ in the central region. Since we expect $\Gamma(K^{*0}(2060)\to\phi K^0)=\Gamma(K^{*+}(2060)\to\phi K^+)$, our $\phi K^{\pm}$ limit implies a limit on ϕK^0,

$$\Gamma(\phi K^0)/\Gamma(\phi K^{*0})=0.11\pm0.19\ ,$$

to be compared[6] with

$$\Gamma(\rho^0K^0)/\Gamma(\rho^0K^{*0})=0.89\pm0.60\ .$$

Alternatively, the latter ratio predicts 297 ± 240 $\phi K^{\pm}$ events from $K^{*\pm}(2060)$ decay, consistent with our 35 ± 58 events. We conclude that strange meson resonances above the ϕK threshold have significant B to ϕKX, comparable to those of ρ^0KX and ωKX.

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