ϕ-meson production in 3.75-GeV/c π^+p interactions

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The production of ϕ mesons is studied in the reaction $\pi^+p \to \pi^+p\ K^+K^-$ and $\pi^+ \to \pi^+p\ K^0\bar{K}^0$ at 3.75 GeV/c. A large isotropic component is seen in the production angular distribution for the reaction $\pi^+p \to \pi^+p\phi$. The cross sections for the $\phi\pi^+p$ and $\phi\Delta^{++}$ final states are compared with the cross sections for $\omega\pi^+p$ and $\omega\Delta^{++}$ at the same momentum.

The ψ mesons are considered to be $c\bar{c}$ bound states, and their narrow widths are interpreted as due to the Zweig-rule suppression of their decay into uncharmed mesons. Similarly, any coupling between the ϕ meson and nonstrange mesons can be considered to occur either through a violation of the Zweig rule[1] or through deviations from ideal ϕ-ω mixing.[2] This similarity between the ψ and ϕ mesons motivates a more detailed study of the production of ϕ mesons by nonstrange hadrons.

In the case of peripheral production by pions, the ϕ is expected to be suppressed relative to the ω by a factor $\tan^2\theta_V$, where θ_V is the deviation from the ideal mixing angle. Experiments[3,4] on the reaction $\pi^-p \to \phi n$ between 3 and 6 GeV/c have found that within their limited acceptance region the ϕ-production angular distribution is rather flat, becoming more peripheral with increasing energy. This is in contrast to the clearly peripheral nature of the reaction $\pi^-p \to \omega n$ in the same energy region. The authors isolate this difference as being in the unnatural-parity-exchange contributions. They find that the natural-parity-exchange production angular distributions of the ϕ and ω are similar and that the corresponding cross sections are in the ratio 0.0023 ± 0.0004 ($|\theta_V| = 2.7° \pm 0.2°$).

In this paper we present measurements of the reaction $\pi^+p \to \phi\pi^+p$ at 3.7 GeV/c, over the entire range of ϕ production angles, and find that the ϕ-production angular distribution has a large isotropic component. As a consequence, the ratio of the cross section for producing $\phi\pi^+p$ to that for producing $\omega\pi^+p$ is almost an order of magnitude greater in the central part of the angular distribution than in the forward direction. We see evidence for $\phi\Delta^{++}$ production and compare the cross section for producing $\phi\Delta^{++}$ with that for $\omega\Delta^{++}$.

The data come from a very large exposure (1.35×10^6 pictures) of the SLAC 82-in. bubble chamber exposed to an rf-separated 3.75 GeV/c π^+ beam. The effective path length corresponds to 28 events/μb. The four-prong events were automatically scanned and measured using the flying-spot digitizer in the DAPR mode. Remeasurements were done on the HAZE and COBWEB system. Geometry and kinematic fitting were done with TVGP and SQUAW. Ionization measurements were used for consistency and ambiguity resolution whenever possible. A confidence-level cut of 0.01 is made on all fits. We study the reactions

$$\pi^+p \to \pi^+pK^+K^-, \quad (1)$$

$$\pi^+p \to \pi^+pK^0\bar{K}^0 \text{ (1 visible } V), \quad (2)$$

$$\pi^+p \to \pi^+pK^0_S\bar{K}^0_S \text{ (2 visible } V). \quad (3)$$

The cross sections for these channels,[5] normalized to the cross section for the reaction $\pi^+p \to \pi^+p\pi^+\pi^-$ at this energy, are given in Table I(a).

TABLE I. Corrected cross sections for (a) reaction channels and (b) ϕ production.

(a) Channel cross sections	
$\pi^+p \to \pi^+pK^+K^-$	120 ± 8 μb
$\pi^+p \to \pi^+pK^0_SK^0_S$	18.5 ± 2 μb
$\pi^+p \to \pi^+pK^0_LK^0_S$	47 ± 9 μb
$\pi^+p \to \pi^+pK^0\bar{K}^0$	84 ± 9.5 μb
(b) ϕ^0 production cross sections	
$\pi^+p \to \phi\pi^+p$ (from $K^0_LK^0_S$)	9.5 ± 2.0 μb
$\pi^+p \to \phi\pi^+p$ (from K^+K^-)	9.3 ± 1.8 μb
$\pi^+p \to \phi\pi^+p$ (both decay modes)	9.4 ± 1.4 μb
$\pi^+p \to \phi\Delta^{++}$ (from $K^0_LK^0_S$)	2.2 ± 1.1 μb
$\pi^+p \to \phi\Delta^{++}$ (from K^+K^-)	1 ± 1 μb
$\pi^+p \to \phi\Delta^{++}$ (both decay modes)	1.5 ± 0.8 μb

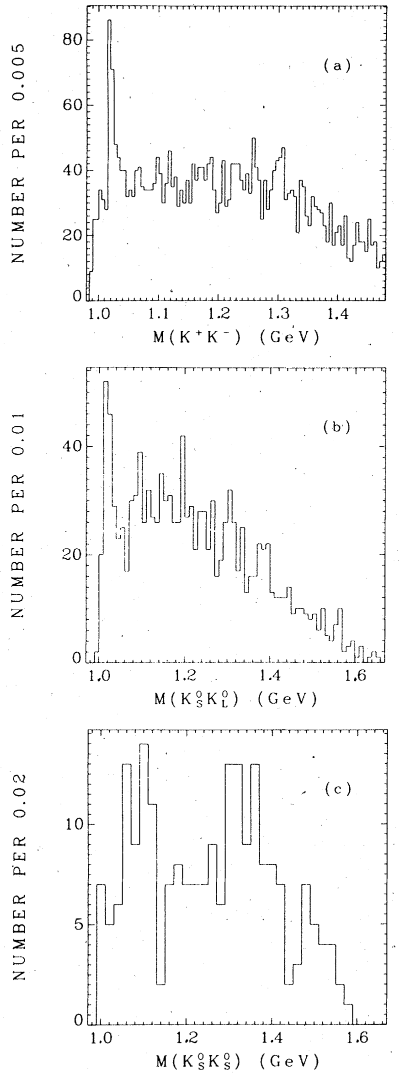

FIG. 1. (a) K^+K^- invariant-mass spectrum in reaction (1); (3624 event). (b) $K^0\overline{K}^0$ invariant-mass spectrum in reaction (2); (1248 events). (c) $K^0\overline{K}^0$ invariant-mass spectrum in reaction (3); (217 events).

In Fig. 1 we show the K^+K^- and $K^0\overline{K}^0$ invariant-mass distributions for reactions (1)–(3). A clear ϕ signal over background is seen in reactions (1) and (2) but not in reaction (3), consistent with the restrictions imposed by the quantum numbers of the ϕ. The agreement between the ϕ production cross sections [Table I(b)] determined separately in reactions (1) and (2) is excellent giving a mean value (corrected for unseen decay modes) of $\sigma(\pi^+p \to \phi\pi^+p) = 9.4 \pm 1.4$ μb. The fitted mass and half width of the ϕ are 1020 ± 0.5 and 4.4 ± 1.5 MeV, respectively. A sizable K^{*0} signal is also seen in the $K^-\pi^+$ and $K^0\pi^+$ mass spectra, but these events are spread rather uniformly over the $K\overline{K}$ mass spectrum and are taken to be a background

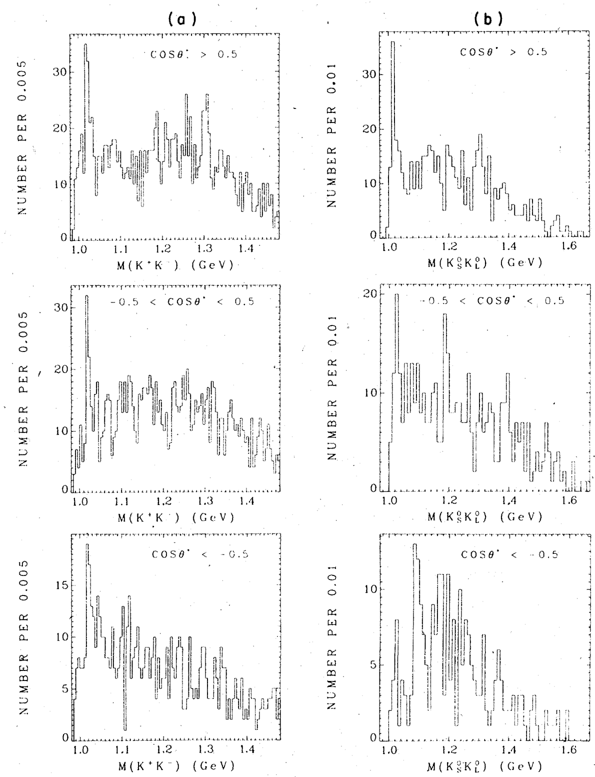

FIG. 2. (a) K^+K^- invariant mass in reaction (1) for production-angle intervals $0.5 < \cos\theta^*_{K\overline{K}} < 1.0$, $-0.5 < \cos\theta^*_{K\overline{K}} < 0.5$, and $-1.0 < \cos\theta^*_{K\overline{K}} < -0.5$; (b) $K^0\overline{K}^0$ invariant mass for reaction (2) in same angular intervals.

contribution in this paper. No $\phi\pi^+$ or ϕp resonances are seen.

To study the ϕ-production angular distribution in reactions (1) and (2), we show the K^+K^- and $K^0\overline{K}^0$ mass spectra for three regions of the $K\overline{K}$ production angle in Fig. 2. *A ϕ signal is seen in all three regions.* We define the interval $1.010 < M(K\overline{K}) < 1.030$ GeV to contain all the ϕ events, and the intervals $1.030 < M(K\overline{K}) < 1.050$ GeV and $0.990 < M(K\overline{K}) < 1.010$ GeV to represent the background. The background-subtracted ϕ-production angular distributions for reactions (1) and (2) (Ref. 7) are then shown in Fig. 3 and indicate a substantial isotropic component in addition to a forward peak.

Since the $\phi N\overline{N}$ coupling is also expected to be suppressed, we have searched for a backward peak in ϕ production. However, given the usual ratio of forward to backward peaks, any backward peak would be masked by the isotropic component. Hence we can only set a 2-standard-deviation upper limit on backward ϕ production in reaction (1); $\sigma < 1.3$ μb in the interval $-1.0 < \cos\theta^* < -0.8$.

The ω production cross sections are already rather peripheral at this energy.[6] In Fig. 4 we

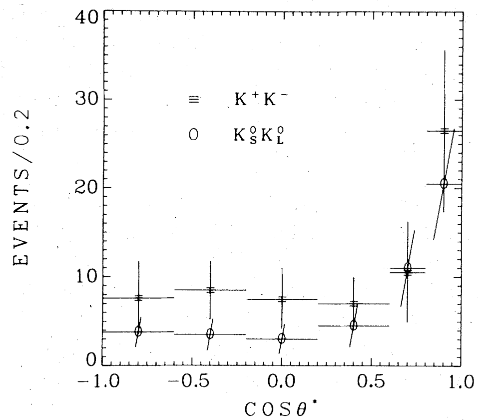

FIG. 3. Background-subtracted ϕ-production angular distribution for reaction (1) and reaction (2).

show the ratio[2]

$$Z \equiv \frac{d\sigma/d\Omega(\pi^+p \to \pi^+p\phi)}{d\sigma/d\Omega(\pi^+p \to \pi^+p\omega)}$$

as a function of $\cos\theta^*$ using ϕ's and ω's produced in the same four-prong event sample. This ratio includes corrections for the unseen decay modes of the ϕ and ω. In the forward direction, these measured values of Z can be compared with the values 0.0079, 0.0052, 0.0029, and 0.0032 observed[3,4] at 3, 4, 5, and 6 GeV/c, respectively, for the corresponding ratio in the forward $\pi^-p \to (\phi, \omega)n$ reactions. An interpolated value of 0.0055 for 3.75 GeV/c is shown as the dotted line in Fig. 4 and agrees with our value of $Z = 0.0044 \pm 0.0011$ over a comparable forward interval in $\cos\theta^*$. While this value of Z in the forward direction is consistent with the usual small deviation from ideal mixing, the larger values of Z observed over most of the angular region cannot be understood in such a simple model.[8]

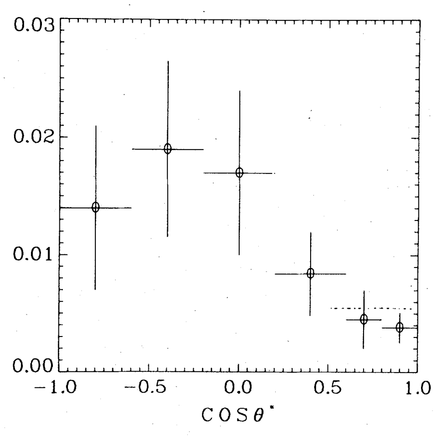

FIG. 4. Production angular distribution of the ratio Z (defined in text).

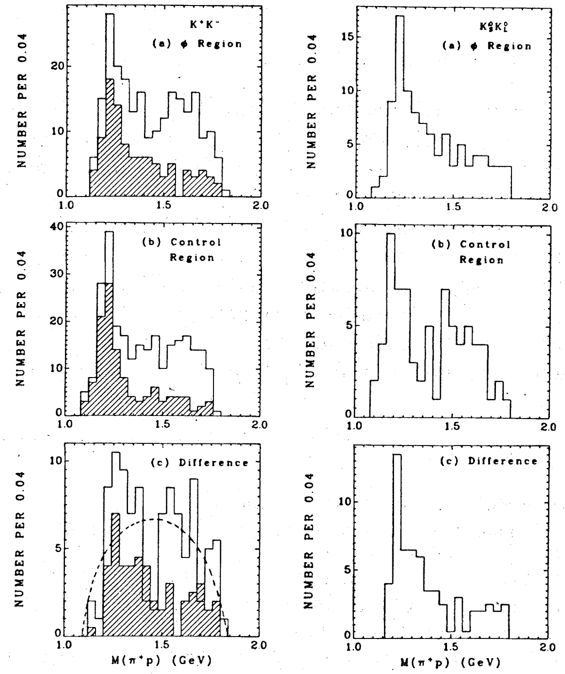

FIG. 5. The recoil π^+p invariant-mass spectra in reactions (1) and (2) for (a) the ϕ band, (b) the background bands, and (c) the difference between (a) and (b).

The π^+p mass spectra for reactions (1) and (2) show a large Δ^{++} signal. Figures 5(a) and 5(b) show the same spectra for the ϕ band and the background bands, as defined above; both show a Δ^{++} signal. By contrast, the difference [Fig. 5(c)] show only a weak Δ^{++}. The phase-space curve shown in Fig. 5(c) is an excellent fit, although K^* decays are expected to modify this background shape. The events in the mass band $1.18 < M(\pi^+p) < 1.26$ GeV for the K^+K^- and $K^0\overline{K}^0$ decay modes of the ϕ provide a mean cross-section measurement of $\sigma(\pi^+p \to \Delta^{++}\phi) = 1.5 \pm 0.8$ μb [Table I(b)].

The ratio of these $\phi\Delta^{++}$-production cross sections to the corresponding $\omega\Delta^{++}$-production cross sections should also be a measure of the ϕ-ω mixing angle:

$$Z' \equiv \frac{\sigma(\pi^+p \to \Delta^{++}\phi)}{\sigma(\pi^+p \to \Delta^{++}\omega)} = 0.0023 \pm 0.0012$$

TABLE II. ϕ-decay density matrix elements in the reaction $\pi^+p \to \phi\pi^+p$; $\phi \to K\overline{K}$ (all).

	All events	$\cos\theta^* > 0.5$
ρ_{00}	0.395 ± 0.042	0.492 ± 0.065
$\rho_{1,-1}$	0.029 ± 0.033	0.033 ± 0.045
$\mathrm{Re}\rho_{10}$	0.037 ± 0.025	0.029 ± 0.034
ρ_+	0.33 ± 0.04	0.26 ± 0.06
$\rho_+/(1-\rho_+)$	0.50 ± 0.09	0.35 ± 0.10

or

$$|\theta_V| = 2.7° \pm 1.4° .$$

Restricting the production angle of the ϕ to the forward quadrant ($\cos\theta^* > 0.5$) gives the recoil spectra shown as the shaded region in Fig.'s 5(a)–5(c).

The ϕ-decay density matrix elements for the combined sample of K^+K^- and $K^0\overline{K}^0$ decays are given in Table II. The combination $\rho_+ \equiv \rho_{11} + \rho_{1,-1}$ is the fraction of natural-parity exchange and $\rho_+/(1-\rho_+)$ is the ratio of the natural-parity-exchange to the unnatural-parity-exchange production. The values of $\rho_{1,-1}$ and $\text{Re}\rho_{10}$ are consistent with zero. The values of ρ_{00} and ρ_+ near the forward direction indicate that there is a substantial unnatural-parity-exchange contribution to the ϕ-production amplitude at this energy. A similar result was obtained for the reaction $\pi^-p \rightarrow \phi n$ in Ref. 3.

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[4]D. Cohen *et al.*, Phys. Rev. Lett. 38, 269 (1977) confirm these results with higher statistics at 6 GeV/c.

[5]For an analysis of the same reactions from a previous 4.4 event/μb exposure, see W. R. Butler *et al.*, Phys. Rev. D 7, 3177 (1973).

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[7]The $K_S^0\overline{K}_S^0$ contribution to reaction (2) as measured by reaction (3) and the K^0-decay losses (5%) do not affect the angular distribution at this level of statistics.

[8]S. Yazaki *et al.* [Phys. Lett. 68B, 251 (1977)] have in fact suggested that relatively copious production of ϕ mesons might be expected in the central region.