ϕ-meson production in the reaction $p_{\uparrow}p \to pK^+K^-p$ at 11.75 GeV/c

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15 000 events of the reaction $p_{\uparrow}p \to pK^+K^-p$ were obtained at 11.75 GeV/c using the Zero Gradient Synchrotron polarized proton beam and the Effective Mass Spectrometer. This event sample includes 1500 events of $p_{\uparrow}p \to p\phi p$. The characteristics of ϕ production are examined. The t distribution is found to be quite shallow (exponential slope parameter 3.3 GeV^{-2}). The cross section for ϕ production is compared to that for $pp \to p\omega p$ measured in the same apparatus. A ratio of ϕ/ω cross sections of 0.010 ± 0.002 is found, substantially larger than the value of 0.002 predicted by the Okubo-Zweig-Iizuka rule. Upper limits are set for the production of narrow states, possibly of a $qqqq\bar{q}$ quark composition, decaying into ϕp, K^+K^-p, or $K^+Y^*(1520)$.

I. INTRODUCTION

We report results based on 15 000 events of the reaction

$$p_{\uparrow}p \to pK^+K^-p \; , \qquad (1)$$

including 1500 events of

$$p_{\uparrow}p \to p\phi p \qquad (2)$$

using the Zero Gradient Synchroton 11.75-GeV/c polarized proton beam and the Effective Mass Spectrometer. Previous studies of exclusive ϕ production in pp interactions have had at most a few hundred events or poor signal-to-background ratio.[1–3] The production of strange particles and of states containing hidden strangeness such as the ϕ is interesting for several reasons. The ideas embodied by the so-called Okubo-Zweig-Iizuka (OZI)[4] rule suggest that in pp or πp collisions, production of the ϕ unaccompanied by additional strange particles should be suppressed relative to production of states not containing strange quarks. If the OZI rule were exact, then ϕ production would proceed only through the small admixture of nonstrange quarks in the ϕ and the ratio of ϕ production to ω production would be only about 0.2%. An earlier experiment at 10 GeV/c suggests[3] that ϕ production in pp interactions (but not in πp) is enhanced by an order of magnitude over this expectation. In the present experiment we have measured the ϕ cross section with better statistics and clean identification of events and have compared the result to ω production cross sections obtained in an experiment using the same apparatus.

Another area of physics illuminated by this experiment is the question of baryon states containing more than three quarks. There has been much speculation concerning the existence of states with $qqqq\bar{q}$ quark composition, but no clear experimental verification.[5–8] Our present experiment produced upper limits of around 10 nb on the production of such states decaying into $p\bar{p}p$.[9] A possible five-quark candidate has been reported with strangeness -1 and mass 3.17 GeV, which decays into multiple strange particles.[10] One might expect a state with quark composition $uuds\bar{s}$ to decay preferentially to ϕp or K^+K^-p. We derive from this experiment sensitive limits on the production of narrow states having such decay modes.

A brief description of the experimental apparatus and methods used to isolate the sample of events of reaction (1) will first be given. Then the cross sections for ϕ production will be presented and compared to ω production. A simple one-pion-exchange model will then be presented and compared to the data. The search for narrow ϕp or K^+K^-p states will then be considered, followed by a short summary.

II. EXPERIMENTAL TECHNIQUE

The experimental apparatus has been described in detail in several previous publications,[11] and only the aspects important for this experiment will be presented here. The incident beam contained 400 000 transversely polarized protons per 800-msec spill at 11.75 GeV/c. The beam polarization was about 60%. For each event of interest, four sets of proportional chambers measured the beam trajectory upstream of the 25-cm liquid hydrogen target. The forward-produced p, K^+, and K^- were measured by the large-aperture magnetic spectrometer.[12] The recoil proton's trajectory was measured by two cylindrical multiwire proportional chambers coaxial with the target.[13] The recoil azimuth ϕ was obtained from hits on the anode wires, which were parallel to the beam, and the recoil polar angle θ was determined by fast delay-line readout of cathode strips perpendicular to the anode wires.

The trigger required a good beam particle (as defined by a counter telescope), no count in a 2.5-cm-square beam-veto counter just downstream of the spectrometer magnet, exactly three hits in the 40-scintillator counter hodoscope downstream of the magnet, no more than one hit in the box of veto counters surrounding the target and recoil detector, hits in at least one anode wire of both the inner and outer proportional chambers of the recoil detector, and no count in the large aperture Čerenkov counter[14] at the downstream end of the experiment. The Čerenkov counter was filled with Freon 12 at 60 psi and had a pion threshold of 1.6 GeV/c.

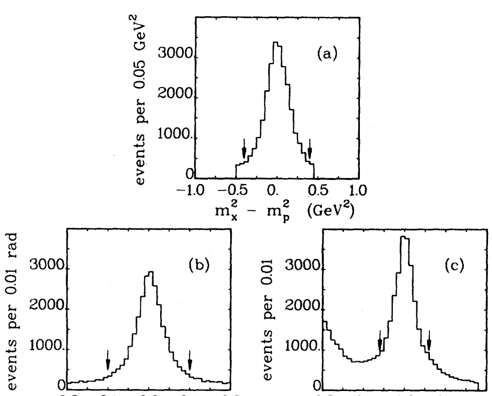

FIG. 1. (a) Distribution of $m_x{}^2-m_p{}^2$ for the hypothesis $pp \to pK^+K^-x$ for events satisfying $|\Delta\phi| < 0.1$ rad and $|\Delta \cot\theta| < 0.06$, where $\Delta\phi$ and $\Delta \cot\theta$ are the differences between measured and predicted recoil proton angles; (b) the $\Delta\phi$ distribution cut on $|m_x{}^2-m_p{}^2| < 0.4$ GeV^2 and $|\Delta \cot\theta| < 0.06$; (c) the $\Delta \cot\theta$ distribution cut on $|m_x{}^2-m_p{}^2| < 0.4$ GeV^2 and $|\Delta\phi| < 0.1$ rad. The arrows show the positions of the cuts.

During the experiment 1.6×10^7 triggers were recorded. After suitable corrections the beam flux of the experiment corresponded to a sensitivity at 100% acceptance of 37.6 events per nb.

After reconstruction of tracks in the spectrometer, events with the desired topology of one negative and two positive tracks were selected for further analysis. At this stage the event sample still consisted predominantly of events of the final state $p\pi^+\pi^-p$, where the pions either had momentum lower than the Čerenkov-counter threshold or missed the aperture of the Čerenkov counter. The three kinematical constraints available (since all momenta except the magnitude of the recoil proton momentum were measured) were applied to separate out the events of reaction (1). Cuts were made on the missing-mass squared of the system recoiling against the forward three particles, and on the differences between the measured values of ϕ and $\cot\theta$ and the values calculated from a one-constraint fit to the three forward tracks. The kinematic calculations were made for both assignments of the positive tracks to the K^+, and the case that best agreed with the K^+K^-p hypothesis was kept. The cuts used were ± 0.4 GeV^2 on the missing mass squared, ± 0.1 rad on $\Delta\phi$, and ± 0.06 on $\Delta \cot\theta$. The missing-mass-squared distribution after the cuts on $\Delta\phi$ and $\Delta \cot\theta$ have been applied is shown in Fig. 1(a), and similarly Figs. 1(b) and 1(c) show the $\Delta\phi$ and $\Delta \cot\theta$ distributions after cuts on the other two quantities. A clear signal for the pK^+K^-p final state is evident. The background in the final event sample is about 30%, varying monotonically from 20% at low K^+K^-p mass to $\sim 50\%$ at 3 GeV K^+K^-p mass.

The complete acceptance-correction procedure used to obtain the cross section and angular-distribution moments has been described in Ref. 11. The Monte Carlo acceptance program generated ϕp events with a flat distribution in ϕp mass and a distribution in the four-momentum transfer t from the beam to the ϕp system that approximately agreed with the t distribution of the raw data. Isotropic angular distributions for the breakup of the ϕp system and the decay $\phi \to K^+K^-$ were used. The generated particles were tracked through the spectrometer and the various trigger requirements and cuts were imposed. The Monte Carlo tracks were not subjected to smearing by multiple scattering or experimental resolution; however, the aperture cuts applied were in all cases more stringent than the actual physical apertures of the spectrometer. These same cuts were applied to the real data and resulted in a rejection of 11% of the ϕp events.

Corrections were made for decay in flight of the K^+ and K^-, and for vetoing of events having kaon momenta greater than K threshold in the Čerenkov counter (5.3 GeV/c); this last effect is negligible for ϕp events, but is important for K^+K^-p events at larger K^+K^- masses.

Because of the limited statistics, the full procedure of unfolding the acceptance-corrected angular-distribution moments, described in Ref. 11, was only done in coarse bins of ϕp mass for all t and in coarse bins of t for all ϕp mass. We used an isotropic angular distribution to calculate the acceptance in more detail as a function of mass and momentum transfer. The alternative procedure of weighting the isotropic acceptance by the average angular distribution changes the calculated acceptance by less than 10%.

Several nongeometric corrections also had to be applied to the data to obtain cross sections. The efficiency of the recoil detector was measured using pp elastic scattering and $pp \to p\pi^+\pi^-p$ events without anode hits required in the trigger and found to be $(93\pm5)\%$. A correction of 9% was made for interactions of the forward particles in the liquid hydrogen target and the material in the spectrometer. A correction of $(9\pm6)\%$ was made for spark-chamber and reconstruction-program inefficiency. We emphasize that these corrections are exactly the same as those used in the measurements of the $pp \to p\omega p$ cross section, and so do not affect the ϕ/ω cross-section ratio.

III. RESULTS

A. Production of ϕ's.

Figure 2 shows the distribution of events in K^+K^- mass, and Fig. 3 shows the same data in finer mass bins in the region around 1.02 GeV. A clear signal for the $\phi(1.02)$ is evident and no signal for other mesons [in particular the $f'(1.5)$] is seen. A fit to the distribution of Fig. 3 with a Breit-Wigner shape smeared by a Gaussian resolution plus a background linear in K^+K^- mass yields, when the width Γ of the ϕ is held fixed at the world-average value of 0.0041 GeV, a ϕ mass of 1.0193 ± 0.0001 GeV and a Gaussian σ of 0.0019 ± 0.0002 GeV. This value of σ is consistent with the mass resolution calculated from the known properties of the apparatus. (If both Γ and σ are allowed to vary, the best fit yields $m_\phi = 1.0193\pm0.0001$ GeV, $\Gamma_\phi = 0.0045\pm0.0007$ GeV, and $\sigma = 0.0017\pm0.0003$ GeV.)

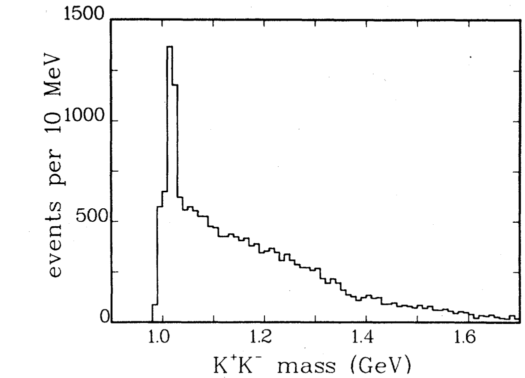

FIG. 2. The K^+K^- effective-mass distribution, not corrected for acceptance, for the final state pK^+K^-p.

The cross section for forward-hemisphere ϕ production in the four-momentum-transfer $-t$ range of 0.075 to 1.0 GeV^2 was determined in four coarse bins of ϕp mass, 1.96 to 2.1, 2.1 to 2.3, 2.3 to 2.5, and 2.5 to 3.0 GeV. The values obtained, after correcting for the $\phi \to K^+K^-$ branching fraction, are 58 ± 5, 102 ± 7, 90 ± 7, and 138 ± 14 nb, respectively. Figure 4 shows these cross sections compared to cross sections for $pp \to p\omega p$ in the same t range, obtained in our previous experiment.[11] The vertical scales of the figure differ by a factor of 100. We see that the ratio of ϕ to ω cross sections is about 0.010 in the mass range 1.95 to 2.5 GeV. The statistical error on the ratio is about 0.002,

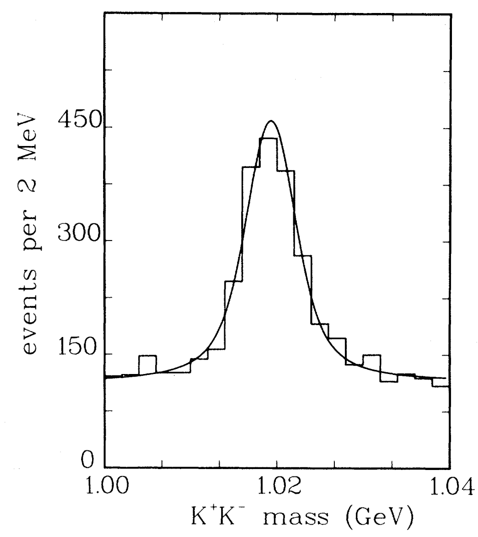

FIG. 3. The K^+K^- effective-mass distribution in 2-MeV bins in the region of the ϕ meson, not corrected for acceptance. The curve shows the results of a fit to a Breit-Wigner shape (with width fixed at 0.0041 GeV) smeared by a Gaussian mass resolution, plus a background linear in mass.

and the systematic errors are estimated to be less than 10%.

The above comparison has been made for definite mass ranges in order to compare ϕ and ω production over comparable regions of phase space. The ratio of ϕ to ω is smaller if all masses are retained in the cross-section comparison, both because the ωp threshold is lower and because the ωp mass distribution is peaked near threshold. The ratio of ϕ to ω cross sections integrated over all masses below 2.5 GeV is 0.0093 ± 0.0021. Alternatively, for the mass range 2.0 to 2.5 GeV, we obtain a ratio of 0.012 ± 0.002. This value is somewhat smaller than the value of 0.02 ± 0.005 (with an additional systematic error of 0.008) obtained by Baldi *et al.*[3] in this mass range at 10 GeV/*c*, although the two measurements are consistent given the large error on the earlier result. The value of near 0.01 is substantially larger than the value of 0.002 expected from the OZI rule. Values consistent with OZI predictions have been observed for the ratio of ϕ to ω production in the reactions $\pi^- p \rightarrow \phi n$ and $\pi^- p \rightarrow \omega n$ at high energies.[15,16]

Figure 5 shows the acceptance-corrected t distribution for ϕ. The t distribution is fairly flat; a fit to e^{Bt} yields $B = 3.28 \pm 0.16$ GeV^{-2}. Figure 6 shows the distribution in Feynman x of the ϕ's. It is flat in the region of small $|x|$ and falls rapidly to zero at large x.

The angular-distribution moments, which were determined in the coarse mass and t bins, as described above, exhibit the following qualitative features (within large statistical uncertainties) in

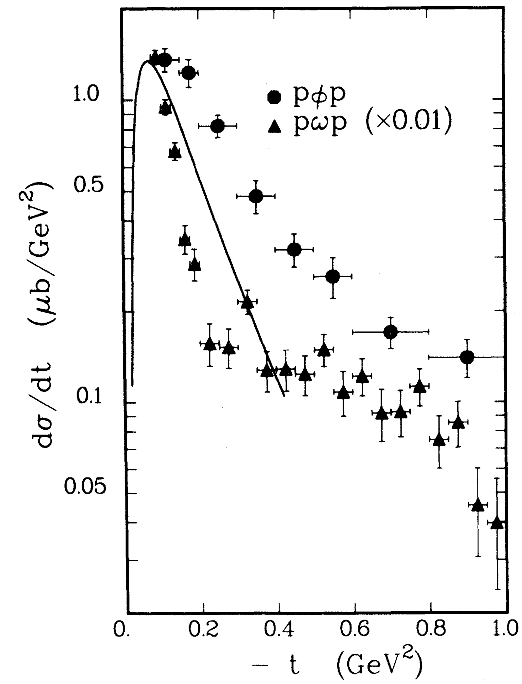

FIG. 5. The distribution in four-momentum transfer t from the beam proton to the ϕp system for the reaction $pp \rightarrow p\phi p$, in the ϕp mass range 1.96 to 3.0 GeV. Acceptance corrections assumed isotropic decays of the ϕp and $\phi \rightarrow K^+K^-$. The distribution for $pp \rightarrow p\omega p$ in the ωp mass range 1.725 to 2.475 GeV is also shown. The line is the result of the OPE-model calculation described in the text.

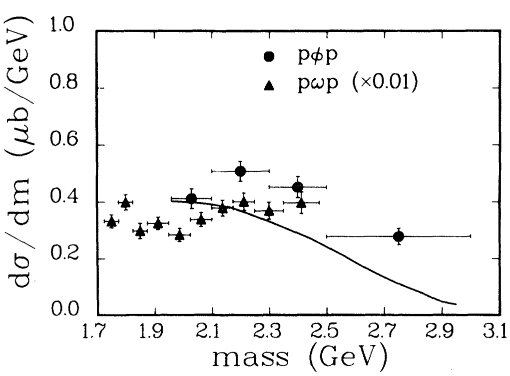

FIG. 4. The cross sections $d\sigma/dm$ for $pp \rightarrow p\phi p$ and $pp \rightarrow p\omega p$ vs the ϕp or ωp mass for the range of momentum transfer $|t|$ 0.075 to 1.0 GeV^2. The ω data are from the experiment described in Ref. 11. The line is the result of the OPE-model calculation described in the text.

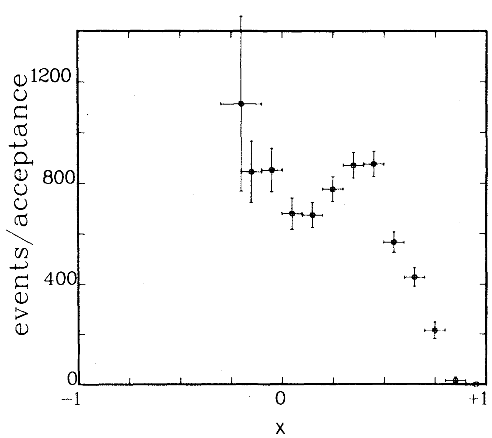

FIG. 6. The distribution in Feynman x of the ϕ in the reaction $pp \rightarrow p\phi p$. Isotropic decays of the ϕp system and $\phi \rightarrow K^+K^-$ were used in calculating the acceptance.

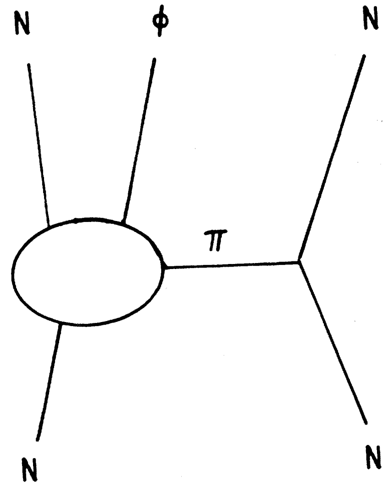

FIG. 7. Graph describing the OPE model of ϕ production.

the mass region near threshold. The unpolarized moments are consistent with isotropic distributions, both in the ϕp breakup (described by angles θ,ϕ) and in the $\phi \to K^+K^-$ decay (described by angles θ' and ϕ'), except for the presence of the moment $\cos 2\phi' d^1_{20}(\theta') d^2_{02}(\theta)$ (called a^2_{22} in Ref. 11). This behavior is consistent with the presence of a strong ϕp S wave having total spin $\frac{3}{2}$. None of the transverse polarization correlations is significantly nonzero, indicating either dominance of a single amplitude or relative phases of 0 or π between different amplitudes.

B. One-pion-exchange model of ϕ production

Deviations from the OZI rule have been observed before, especially at low energies. For example, the ratio $\sigma(\pi^- p \to \phi n)/\sigma(\pi^- p \to \omega n)$ has been measured[17] to be $\sim \frac{1}{60}$ for $p_{\rm lab} = 2$ GeV/c. The OZI rule predicts this ration to be $\sim \frac{1}{500}$. The experimentally observed values tend to this number only at high energies.[15,16]

It is possible to formulate a simple one-pion-exchange (OPE) model for $pp \to p\phi p$ that uses as input data for $\pi^- p \to \phi n$. The model accounts for about half of $\sigma(pp \to p\phi p)$, as well as for the large deviation from the predictions derived from the ω-ϕ mixing angle and the OZI rule. It is described in Fig. 7 and is summarized by

$$\frac{d\sigma}{dt\,dM^2} = \frac{1}{16\pi(2mp_{\rm lab})^2}\lambda^{1/2}(M^2,m^2,\mu^2) \times \sigma(M^2)\frac{g^2}{4\pi}\frac{-4t}{(t-\mu^2)^2}e^{a(t-\mu^2)} . \qquad (3)$$

The symbols in the above equation have the following meaning: M is the mass of the ϕp system; t is the momentum transfer to the ϕp system; m and μ are the masses of the nucleon and pion, respectively; $\sigma(M^2)$ is the cross section for $\pi^0 p \to \phi p$ at center-of-mass energy M; $g^2/4\pi = 14.5$ is the pion-nucleon coupling constant; and λ is the standard kinematical triangle function.

The cross section $\sigma(\pi^0 p \to \phi p)$ is obtained from the measured[15–17] $\sigma(\pi^- p \to \phi n)$ by means of an isospin rotation, $\sigma(\phi p) = \frac{1}{2}\sigma(\phi n)$. Aside from the exponential damping $e^{a(t-\mu^2)}$, no corrections for off-shell behavior of the pion were made in computing the curves. In accordance with the observed behavior of excitation by pions of masses in a similar range,[18] the coefficient a in the exponential was taken to be $a = 5$ GeV^{-2}.

The contribution of this mechanism to the measured cross sections is shown in Figs. 4 and 5.[19] It can be seen that about half of the ϕ cross section is accounted for by this simple OPE model. The mass distribution is well described in shape. The t distribution, on the other hand, is satisfactorily predicted at small t values (where pion exchange is expected to dominate), but fails for $-t \geq 0.15$ GeV^2. It is not unreasonable to speculate that other exchanges that have large couplings to $N\bar{N}$, such as f and ω, produce similar excitations of the ϕp system, and contribute the rest of the cross section. As a function of mass (Fig. 4), the ω/ϕ ratio seems to follow the same trend as for

$$\frac{\sigma(\pi^- p \to \omega n)}{\sigma(\pi^- p \to \phi n)} .$$

By itself, this would be consistent with a model in which both ϕ and ω production are dominated by

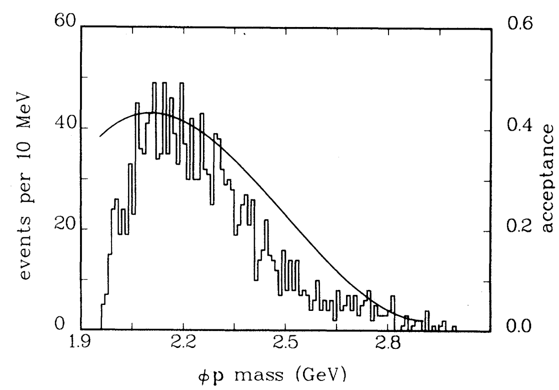

FIG. 8. The ϕp mass distribution for the $|t|$ range 0.075 to 1.0 GeV^2. The ϕ was defined by the K^+K^- mass cut 1.014 to 1.024 GeV. The curve (right scale) shows the acceptance weighted by the angular distribution of the whole sample of ϕp events.

TABLE I. Five-standard-deviation upper limits for forward-hemisphere production of resonances with width $\Gamma = 10$ MeV and decaying into ϕp, K^+K^-p, or $K^+Y^*(1520)$.

Mass (GeV)	ϕp	Limit (nb) K^+K^-p	$K^+Y^*(1520)$
2.0	14	10	
2.2	19	50	41
2.4	18	75	50
2.6	19	78	47
2.8		89	50

π exchange. However, as shown in Fig. 5, the ϕ and ω t distributions are markedly different and suggest quite different production mechanisms (e.g., mainly ω exchange for ω production,[11] and a mixture of π and other exchanges for ϕ production).

We also remark that the x dependence shown in Fig. 6 can be reasonably well accounted for as a kinematical reflection of the flat ϕp mass distribution, the exponential damping of the momentum transfer to ϕp, and the approximately isotropic decay distribution of the ϕ in the ϕp rest frame.

C. Production of narrow resonances

Figure 8 shows the raw ϕp mass distribution in 10 MeV bins and the calculated acceptance. The ϕ has been defined as K^+K^- mass between 1.014 and 1.024 GeV. The mass resolution calculated from the known properties of the spectrometer is always smaller than the 10-MeV bin width. No evidence for narrow resonances is seen. We have calculated five standard deviation upper limits for the production of a state of width 10 MeV with subsequent decay to ϕp. The results are shown in Table I for several ϕp masses. We see that limits of about 20 nb are set over the entire mass range.

One may also search for narrow structures without requiring that the K^+K^- come from ϕ decay. Figure 9 shows the K^+K^-p mass distribution in 10 MeV bins, along with the acceptance. The acceptance was calculated assuming a flat distribution in K^+K^- mass, isotropic decay distributions, and a t distribution approximately that observed in the raw data. Again no evidence is seen for narrow resonances. Limits are given in Table I.

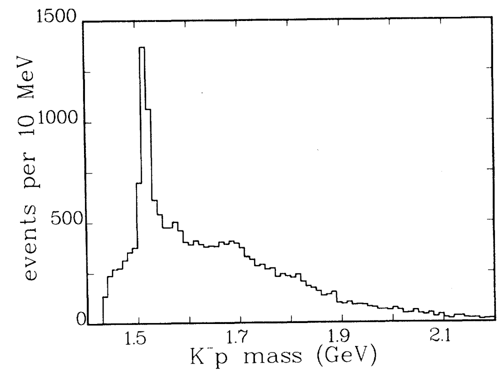

FIG. 10. The K^-p mass distribution in $pp \rightarrow pK^+K^-p$ for the $|t|$ range 0.075 to 1.0 GeV^2.

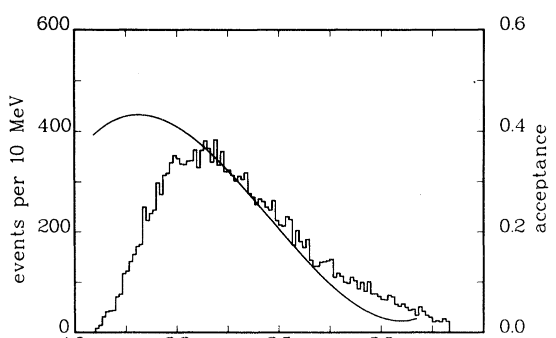

FIG. 9. The K^+K^- mass distribution for the $|t|$ range 0.075 to 1.0 GeV^2. The curve shows the acceptance for isotropic angular distributions.

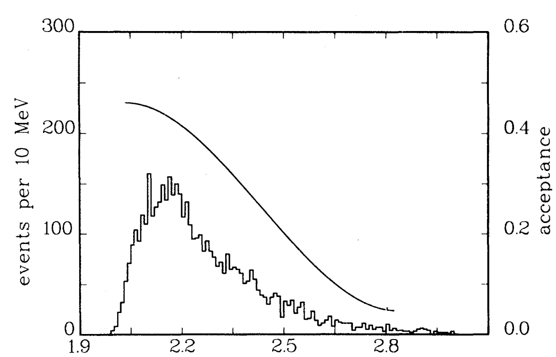

FIG. 11. The mass distribution of $K^+Y^*(1520)$ for the $|t|$ range 0.075 to 1.0 GeV^2. The $Y^*(1520)$ was defined by $1.49 < m_{K^-p} < 1.55$ GeV. The curve shows the acceptance for isotropic angular distributions.

It is possible that $qqqq\bar{q}$ states might be more strongly coupled to a K and a hyperon resonance than to a ϕ plus proton. We have looked for such decays. Figure 10 shows the K^-p effective-mass distribution of the data. A prominent signal of the $Y^*(1520)$ is evident. Figure 11 shows the $Y^*(1520)K^+$ mass distribution, where the mass region 1.49 to 1.55 GeV has been used to select $Y^*(1520)$'s. The acceptance curve shown in the figure is based on isotropic decays of the Y^*K^+ and $Y^* \to K^-p$ systems. Again we see no evidence for narrow structures, and 5-standard-deviation upper limits are listed in Table I. (The one-bin fluctuation at 2.105 GeV has a significance slightly under 4 standard deviations.) We have also examined the K^+p mass distribution and see no significant structure.

IV. SUMMARY

Using a transversely polarized proton beam at 11.75 GeV/c incident on a liquid hydrogen target, a sample of 15 000 events of the reaction $pp \to pK^+K^-p$ has been obtained. This sample includes 1500 events of $pp \to p\phi p$. The forward hemisphere cross section for ϕ production has been measured to be 388 ± 18 nb for the range $m_{\phi p} < 3$ GeV, and $0.075 < |t| < 1.0$ GeV^2. By comparing to an experiment measuring $pp \to p\omega p$ using the same apparatus, the ratio of ϕ to ω production is found to be 0.010 ± 0.002, considerably in excess of the 0.002 expected from the OZI rule and the $u\bar{u}+d\bar{d}$ content of the ϕ. The ϕ production is found to have a rather flat t dependence (exponential slope parameter 3.3 ± 0.2 GeV^{-2}). The x distribution is found to be flat near $x = 0$, falling to zero as x approaches 1.

Low-mass systems that decay into ϕp violating the OZI rule have been observed before in πp collisions. A simple one-pion-exchange model accounts for a large fraction of the violation of the OZI rule observed here for $pp \to p\phi p$ if data for $\pi N \to \phi N$ are used as input.

Searches have been made for narrow resonances, possibly $qqqs\bar{s}$ states, decaying to ϕp, K^+K^-p, or $Y^*(1520)K^+$. Five-standard-deviation upper limits in the range 20 to 100 nb have been set for the production of such states.

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[18]The t dependence of pion exchange at large masses has been obtained from preliminary results of a study of $pp \to pn\pi^+$ at $3-12$ GeV/c; A. B. Wicklund *et al.*, (unpublished).
[19]In order to obtain the curves in the figures, $d\sigma/dt(\pi^- p \to \phi n)$ was integrated over the full t range assuming the t dependence given in Ref. 15. The slope parameter for $p_{\rm lab} = 4$ GeV/c was taken to be the same as for $p_{\rm lab} = 3$ GeV/c.