Dr. K. W. Lai. We also thank the alternating-gradient synchrotron and 80-in. bubble-chamber staffs and crews for their help in obtaining the pictures, and our scanning, measuring, and data-handling personnel for their efforts.

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[1]J. Bartsch *et al.*, Phys. Lett. 22, 357 (1966), and Nucl. Phys. B8, 9 (1968).

[2]D. Denegri *et al.*, Phys. Rev. Lett. 20, 1194 (1968); J. Berlinghieri *et al.*, Phys. Rev. Lett. 18, 1087 (1967); M. Jobes *et al.*, Phys. Lett. 26B, 49 (1967); J. Andrews *et al.*, Phys. Rev. Lett. 22, 731 (1969).

[3]A. Barbaro-Galtieri *et al.*, Phys. Rev. Lett. 22, 1207 (1969).

[4]The Breit-Wigner parametrization of the Q, and the phase-space amplitude, should be considered as only a rough approximation of the background. We have proceeded in this fashion in order to remove the uncertainty associated with drawing smooth hand-drawn backgrounds, and even though we expect its production, we have not included a $K(1420)$ amplitude. The Q parameters determined by the fit are $M=(1260 \pm 10)$ and $\Gamma=(340 \pm 25)$ MeV, while the mass and width used for the L meson were taken from the results of the fit to the $K\pi\pi$ mass spectrum of Fig. 2(a).

[5]The likelihood function included amplitudes for $K(890)$, $K(1420)$, and phase space.

[6]This branching ratio is obtained by solving for α in the following set of equations:

$$N_{1420}{}^{L}=\alpha N_{L}{}^{L}+\beta N_{bkg}{}^{L}, \quad N_{1420}{}^{c}=\alpha N_{L}{}^{c}+\beta N_{bkg}{}^{c},$$

where $N_{1420}{}^{L}$, $N_{L}{}^{L}$, and $N_{bkg}{}^{L}$ are the number of $K(1420)\pi$ events, the number of L events, and the number of background events, respectively, in the L region. $N_{1420}{}^{c}$, $N_{L}{}^{c}$, and $N_{bkg}{}^{c}$ are the corresponding numbers in the adjacent (control) mass regions to the L; α is the L-branching fraction, while β is the background "branching fraction" into $K(1420)\pi$. We assume that β is constant through the $K\pi\pi$ mass regions. $N_{1420}{}^{L}$ ($N_{1420}{}^{c}$) is obtained by the maximum-likelihood fit to the $K^-\pi^+$ mass projection. $N_{L}{}^{L}$ ($N_{L}{}^{c}$) is obtained from the L Breit-Wigner resonant shape. $N_{bkg}{}^{L}$ ($N_{bkg}{}^{c}$) is obtained by subtracting $N_{L}{}^{L}$ ($N_{L}{}^{c}$) from the total number of events in the region.

[7]The following mass intervals define the resonance regions:

φ, $1.0 \le M(K^+K^-) \le 1.04$ GeV;

η, $0.53 \le M(\pi^+\pi^-\pi^0) \le 0.57$ GeV;

ω, $0.75 \le M(\pi^+\pi^-\pi^0) \le 0.81$ GeV.

[8]We use the term "kinematic enhancements" to refer to $K\pi\pi$ peaks which are not associated with $K\pi$ resonance formation but are due to the general behavior of the $K\pi$ background.

[9]The effect is more pronounced if a momentum-transfer selection is imposed in order to enhance the peripherally produced Q meson.

OBSERVATION OF Σ RESONANCES IN THE 1670-MeV MASS REGION*

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We present confirmation for the existence of two $\Sigma(1670)$ resonances on the basis of their different production angular distributions. One of these decays predominantly into $\Lambda(1405)\pi$ and is produced much more peripherally than the second, whose principal decay mode is $\Sigma\pi$.

The investigation of hyperon resonances in the mass region 1600-1700 MeV has proved fruitful and yet confusing.[1] In the particular case of Σ resonances, this has involved the question of the number of such resonances, their spin-parity, as well as their branching fractions into various decay channels. The history of the $\Sigma(1670)$ is replete with such problems. Experimentally such a state has been observed to decay via the $\Sigma\pi$, $\Sigma\pi\pi$, and $\Lambda\pi$ modes. However, the relative frequency of such decays in production experiments varies with the incoming energy, and in formation experiments[2] only the $\Sigma\pi$ mode, and to a lesser extent the $\Lambda\pi$ decay, have been observed. Recently, Eberhard et al.[3] have presented strong evidence for the existence of two distinct $\Sigma(1670)$

resonances on the basis of the difference between the $\Sigma\pi$- and $\Sigma\pi\pi$-production angular distributions. In this Letter we present evidence confirming this difference in the $\Sigma\pi$ and $\Sigma\pi\pi$ modes in the 1670-MeV mass region, and thereby the two-resonance hypothesis.

The present data have been obtained from an exposure of the 80-in. BNL hydrogen-filled bubble chamber to separated K^- beams from the alternating-gradient synchrotron, with momenta of 3.9 and 4.6 GeV/c.[4] This involved a total of 200 000 pictures at 3.9 GeV/c and 300 000 pictures at 4.6 GeV/c. The main topologies of interest for this study were the events consisting of four prongs plus kink ($\Sigma^\pm$ events) and those with two prongs plus V (Λ^0 and K^0 events).[5] The

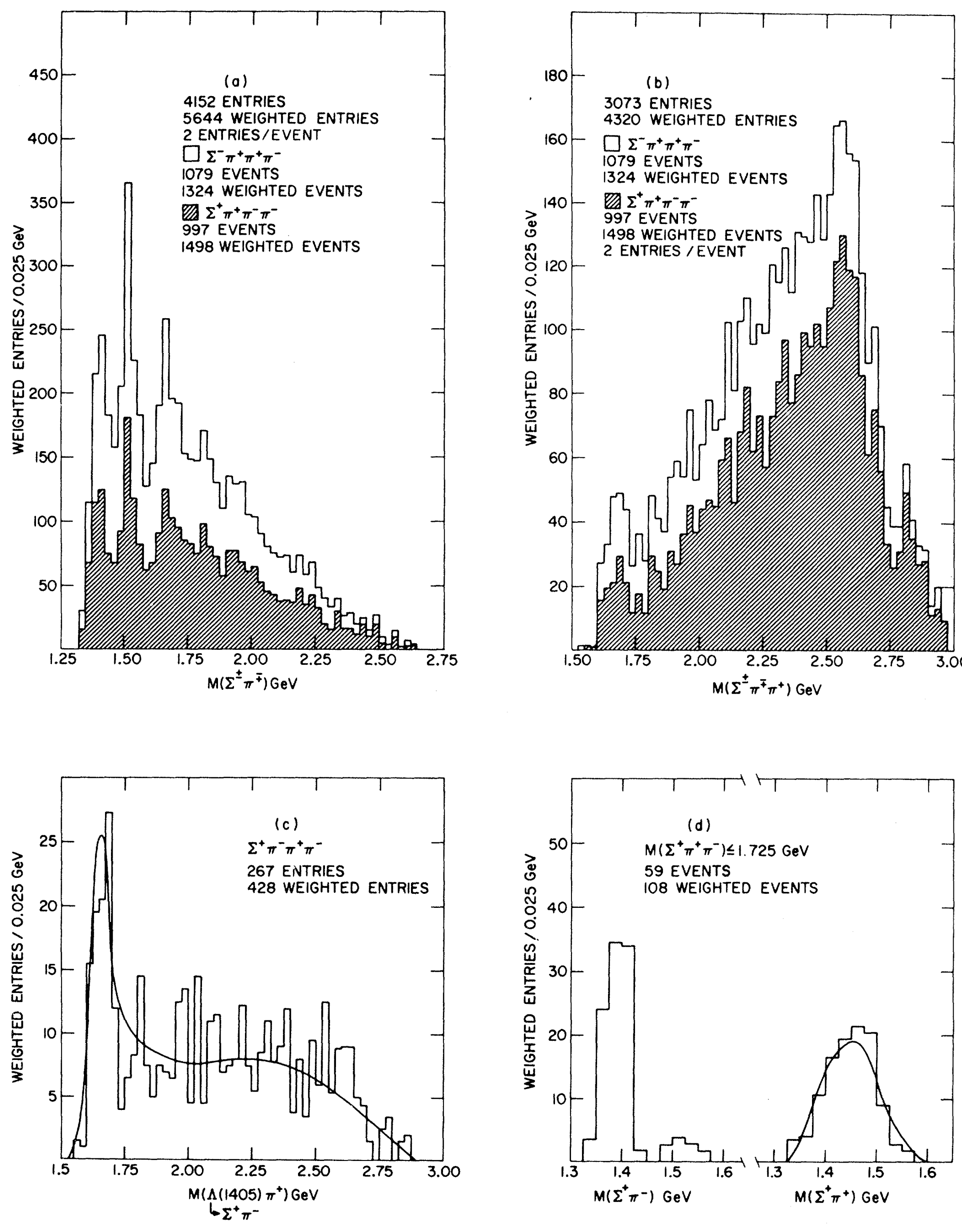

FIG. 1 (a) $\Sigma^\pm\pi^\mp$ effective-mass spectrum from Reactions (a) (shaded) and (2). (b) $\Sigma^\pm\pi^\mp\pi^+$ effective-mass spectrum from Reactions (1) (shaded) and (2). (c) $\Sigma^+\pi^-\pi^+$ effective-mass spectrum from Reaction (1) with the restriction that the $\Sigma^+\pi^-$ form a $\Lambda(1405)$. The solid curve shows a fit of a Breit-Wigner shape and phase space. (d) The $\Sigma^+\pi^-$ and $\Sigma^+\pi^+$ effective-mass spectra from events with $\Sigma^+\pi^+\pi^-$ effective mass in the $\Sigma(1670)$ region. The solid curve is phase-space normalized to the total number of events.

events were measured on the Brookhaven flying-spot digitizer and reconstructed using the Brookhaven versions of TVGP and SQUAW. Ambiguities were resolved whenever possible by using the ionization measurements given by the flying-spot digitizer. The reactions of relevance to this study are

$$K^-p \to \Sigma^+\pi^+\pi^-\pi^-, \quad 997 \text{ events}; \tag{1}$$

$$K^-p \to \Sigma^-\pi^-\pi^+\pi^+, \quad 1079 \text{ events}; \tag{2}$$

$$K^-p \to \Sigma^0\pi^+\pi^-, \quad 813 \text{ events}. \tag{3}$$

The numbers of events indicated are those within suitable fiducial regions for both production and decay vertices. Events have been weighted to allow for losses of short decays and for decays out of the fiducial region.[6] In order to calculate branching ratios, an additional correction was made for small-angle $\Sigma^\pm$ decays, involving average weights of 1.04 for $\Sigma^- \to n\pi^-$, 1.09 for $\Sigma^+ \to n\pi^+$, and 1.85 for $\Sigma^+ \to p\pi^0$.

We have investigated Reactions (1) and (2) for evidence of $\Sigma(1670)$ production. These reactions are dominated by strong production of $\Lambda(1405)$, $\Lambda(1520)$, and an enhancement at a mass of ~1670 MeV in the $\Sigma^\pm\pi^\mp$ mass spectrum [Fig. 1(a)] as well as ρ^0 production in the $\pi\pi$ system (not shown).[7] Figure 1(b) shows the $\Sigma^\pm\pi^\mp\pi^+$ mass spectrum from

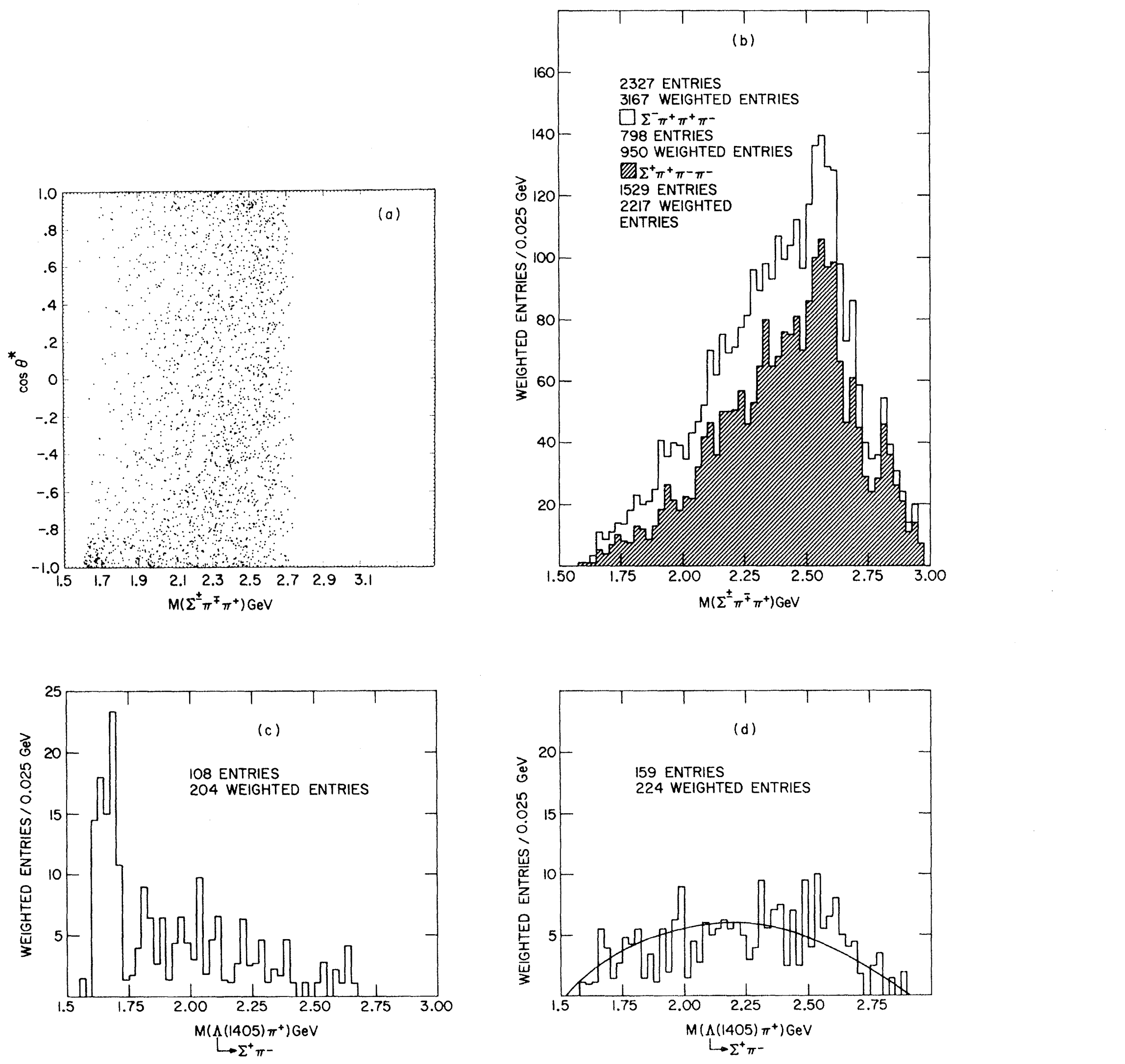

FIG. 2. (a) Two-dimensional distribution of $\cos\theta^*$ vs $M(\Sigma^\pm\pi^\mp\pi^+)$ for events of Reactions (1) and (2). (b) $\Sigma^\pm\pi^\mp\pi^+$ effective-mass spectrum from Reactions (1) (shaded) and (2) with the restriction $\cos\theta^* > -0.7$. (c) $\Sigma^+\pi^-\pi^+$ effective-mass spectrum from Reaction (1) with the $\Sigma^+\pi^-$ required to form a $\Lambda(1405)$ and $\cos\theta^* < -0.7$. (d) Same as (c) but with $\cos\theta^* > -0.7$.

Reactions (1) and (2) in which an enhancement is observed at a mass of ~1670 MeV above a small background. The shaded area represents the mass distribution for only Reaction (1), and a corresponding strong signal appears above background in the same mass region. To study the nature of this enhancement, we have replotted the same mass distribution after requiring the $\Sigma^+\pi^-$ mass to lie in the $\Lambda(1405)$ band, defined as the $\Sigma^+\pi^-$ mass region from $\Sigma\pi$ threshold up to 1460 MeV. This distribution is shown in Fig. 1(c). We notice that the peak at 1670 MeV does not significantly decrease in size, which is consistent with 100% decay of the resonance into $\Lambda(1405)\pi$. The corresponding $\Lambda(1405)\pi$ mass spectrum for Reaction (2) also shows a large enhancement in the 1670-MeV mass region. However, in this reaction, the Σ^- can form a $\Lambda(1405)$ with either of the two π^+'s, and the two $\Lambda(1405)$ bands overlap when the effective mass of the $\Sigma^-\pi^+\pi^+$ system lies in the mass region 1600-1700 MeV. Thus the peak at 1670 MeV may be caused by interference between the two $\Lambda(1405)$ resonance amplitudes. This problem is not present in Reaction (1) which is therefore a more appropriate reaction for investigating a $\Lambda(1405)\pi$ decay mode of the $\Sigma(1670)$. The large signal-to-noise ratio in this mass spectrum allows for the best determination of the $\Sigma(1670)\rightarrow\Sigma\pi\pi$ resonance parameters. The solid curve in Fig. 1(c) shows the result of a maximum-likelihood fit[8] using an incoherent superposition of Breit-Wigner and phase-space amplitudes. The following values of mass and width are obtained:

$$M = 1668 \pm 10 \text{ MeV},$$

$$\Gamma = 135^{+40}_{-30} \text{ MeV}.$$

Further demonstration of a predominant $\Lambda(1405)\pi$ decay mode of $\Sigma(1670)$ is shown in Fig. 1(d) in which the $\Sigma^+\pi^-$ and $\Sigma^+\pi^+$ mass projections of the $\Sigma\pi\pi$-decay Dalitz plot for the region 1.55-1.725 GeV are presented. A large $\Lambda(1405)$ signal appears in the $\Sigma^+\pi^-$ distribution, whereas the $\Sigma^+\pi^+$ mass spectrum is well represented by a phase-space shape.

Having shown the consistency of our data with the existence of a large $\Lambda(1405)\pi$ decay mode of

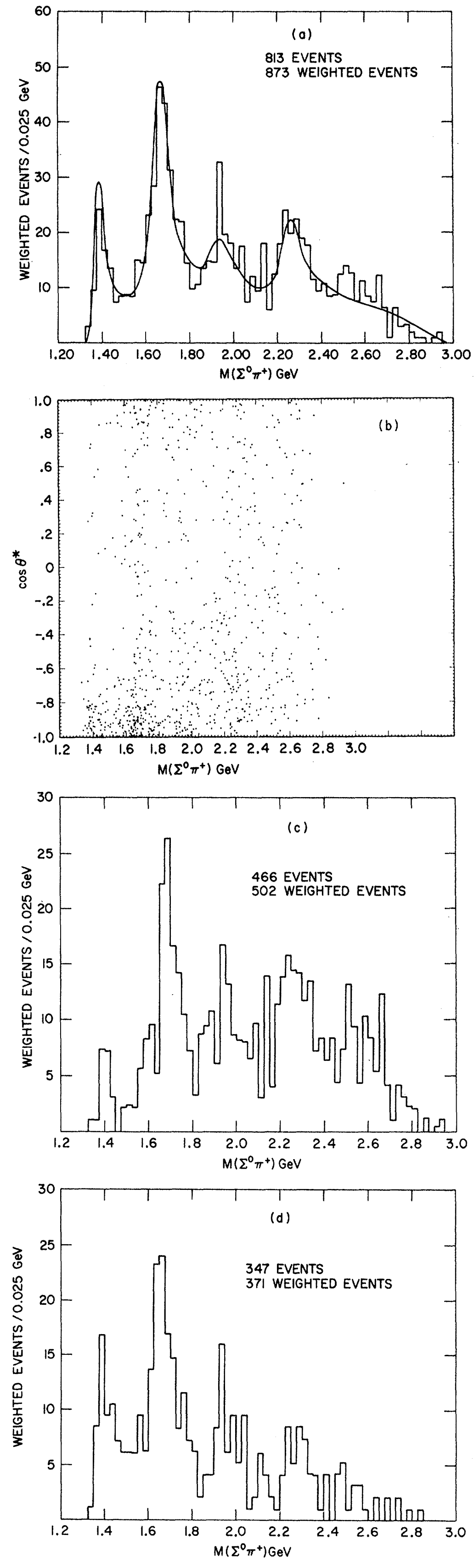

FIG. 3. (a) $\Sigma^0\pi^+$ effective-mass spectrum from Reaction (3). The solid curve is described in the text. (b) Two-dimensional distribution of $\cos\theta^*$ vs $M(\Sigma^0\pi^+)$ for events of Reaction (3). (c) $\Sigma^0\pi^+$ effective-mass spectrum from Reaction (3) with $\cos\theta^* > -0.7$. (d) Same as (c) but with $\cos\theta^* < -0.7$.

Table I. Results of the analysis of the $\Sigma^0\pi^+\pi^-$ final state.

Resonance	Mass (MeV)	Width (MeV)	Percentage Total sample	$\cos\theta^* < -0.7$	$\cos\theta^* > -0.7$
$\Sigma(1385)$	1390 ± 6	33 ± 12	5.6 ± 1.1	11.7 ± 2.4	2.7 ± 1.0
$\Sigma(1670)$	1670 ± 6	110 ± 12	25.9 ± 2.3	37.2 ± 3.5	18.9 ± 2.9
$\Sigma(1940)$	1940 ± 11	90 ± 20	4.5 ± 1.6	3.7 ± 2.3	6.2 ± 2.3
$\Sigma(2280)$	2280 ± 14	100 ± 20	7.8 ± 1.8	6.4 ± 2.4	9.9 ± 2.8
ρ	756 ± 9	157 ± 22	29.6 ± 2.7	22.1 ± 4.0	33.9 ± 3.8
f^0	1265 ± 16	141 ± 35	10.2 ± 2.2	3.2 ± 2.7	13.7 ± 3.0

$\Sigma(1670)$, we now turn our attention to the production angular distribution of this decay. Figure 2(a) is a two-dimensional distribution of $\cos\theta^*$ (θ^* is the scattering angle between incident K^- and outgoing $\Sigma\pi\pi$ system in the overall center of mass) vs $M(\Sigma^\pm\pi^\mp\pi^+)$. The $\Sigma(1670)$ is produced peripherally with little or no signal in the interval $\cos\theta^* > -0.7$ as shown in Fig. 2(b). The $\Lambda(1405)\pi$ effective-mass distribution from (1) for $\cos\theta^* < -0.7$ (≥ -0.7) is shown in Fig. 2(c) [2(d)]. As a measure of the peripherality of the $\Sigma(1670)$, and in order to perform a quantitative test of the difference between the $\Sigma(1670) \to \Sigma\pi\pi$ and $\Sigma(1670) \to \Sigma\pi$ production angular distributions, we have calculated the fraction α defined as

$$\alpha = B/(F+B), \qquad (4)$$

where B (F) is the number of $\Sigma(1670)$ events with $\cos\theta^* \geq -0.7$ (< -0.7). From an estimate of $\Sigma(1670) \to \Lambda(1405)\pi^+$ events above a phase-space background (normalized to the total number of events) in Fig. 2(d) for $M(\Sigma^+\pi^+\pi^-) < 1.725$ GeV, and with the number from the fit to Fig. 1(c) for the same mass interval, we obtain[9]

$$\alpha(\Sigma\pi\pi) = 0.00 \pm 0.04.$$

We now discuss Reaction (3).[10] In Fig. 3(a) we show the $\Sigma^0\pi^+$ effective-mass distribution. We observe that a main feature of this reaction is the production of a $\Sigma(1670)$ resonance whose mass and width are consistent with the values obtained for the resonance coupled to the $\Sigma\pi\pi$ final state. Besides resonances in the $\Sigma^0\pi^+$ system there is also copious ρ and f^0 in the $\pi\pi$ final state. In order to obtain the amount of resonance production, we have performed a maximum-likelihood fit which includes $\Sigma(1385)$, $\Sigma(1670)$, $\Sigma(1940)$, $\Sigma(2280)$, ρ, f^0, and phase space. The resonance parameters are given in Table I, together with the results of the fit.

We have analyzed the production properties of the $\Sigma(1670) \to \Sigma^0\pi^+$ in a way similar to the one described for the $\Sigma\pi\pi$ resonance. Figure 3(b) shows the corresponding $\cos\theta^*$-$M(\Sigma^0\pi^+)$ distribution, and the $\Sigma(1670)$ effect is seen to extend along the complete band of $\cos\theta^*$. The $\Sigma^0\pi^+$ mass projection for $\cos\theta^* > -0.7$ (≤ -0.7) is shown in Fig. 3(c) [3(d)]. To determine the amount of resonant production we have again performed a likelihood fit to the $\Sigma^0\pi^+\pi^-$ reaction for both intervals of $\cos\theta^*$. The results of the fits are displayed in Table I. The ratio $\alpha(\Sigma^0\pi^+)$ is found to be

$$\alpha(\Sigma^0\pi^+) = 0.42 \pm 0.08,$$

so that the difference in the production angular distribution between the $\Sigma\pi\pi$ and $\Sigma\pi$ resonances is about a 4-standard-deviation effect.[11] This result has now been observed at very different incident momenta (2.7 and 3.9-4.6 GeV/c), and it is therefore unlikely that the effect can be explained as a result of an interference of a single resonance with the background, the latter being very different at the two energies. Thus we con clude that two $I=1$ resonances are present in the 1670-MeV mass region, which confirms the observation of Eberhard et al.[3]

The support of Dr. R. P. Shutt is gratefully acknowledged. We also thank the alternating-gradient synchrotron and 80-in. bubble chamber staffs and crews for their help in obtaining the pictures, and our scanning, measuring, and data-handling personnel for their efforts.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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[1]R. D. Tripp, in *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968,* edited by J. Prentki and J. Steinberger (CERN Scientific Information

Service, Geneva, Switzerland, 1968), p. 173.

[2]R. Armenteros *et al.*, Phys. Lett. 28B, 521 (1969), and references therein.

[3]P. Eberhard, J. H. Friedman, M. Pripstein, and R. R. Ross, Phys. Rev. Lett. 22, 200 (1969).

[4]The results are presented for the combined data at 3.9 and 4.6 GeV/c. A similar analysis at each momentum separately shows results which are consistent with those obtained for the total sample.

[5]The film coverage is different for the two topologies.

[6]In each figure we indicate the sum of weights as well as the number of events.

[7]In order to investigate the reflections of the ρ we have performed a similar study after antiselection of $\Sigma\pi p$ events; the result of the present analysis remains the same.

[8]The minimization program used for the fits was the CERN program MINUIT, written by F. James.

[9]We have presented the analysis for only the $\Lambda(1405)\pi$ events of Reaction (1) because the large resonance signal-to-noise ratio allows less uncertainty in the estimation of the background. The study of the $\Sigma(1670) \to \Sigma^{\pm}\pi^{\mp}\pi^{+}$ produces a consistent result, as is easily seen by a comparison between Fig. 2(b) and Fig. 1(b); however, there is a larger systematic uncertainty in the background estimate.

[10]The separation of the $\Sigma^0\pi^+\pi^-$ and $\Lambda^0\pi^+\pi^-$ final states has been discussed by V. E. Barnes *et al.*, Phys. Rev. Lett. 22, 479 (1969).

[11]We also observe a different energy behavior of the $\Sigma\pi$ and $\Sigma\pi\pi$ resonance-production cross sections, suggesting the two-resonance hypothesis. The values obtained are

$\sigma(\Sigma^0\pi^+) = 28 \pm 5\ \mu\text{b}$,

$\sigma(\Sigma^+\pi^+\pi^-) = 22 \pm 4\ \mu\text{b}$ at 3.9 GeV/c;

and

$\sigma(\Sigma^0\pi^+) = 25 \pm 4\ \mu\text{b}$,

$\sigma(\Sigma^+\pi^+\pi^-) = 7 \pm 3\ \mu\text{b}$ at 4.6 GeV/c.

HEAVY-BOSON PRODUCTION IN $\bar{p}p$ MULTIPION ANNIHILATION AT 6.4 GeV/c

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Production of heavy bosons is studied in $\bar{p}p$ six-prong annihilations at 6.94 GeV/c. Evidence is presented for the existence of a heavy boson with a mass of 3.035 GeV and a full width of 0.200 GeV decaying into four and six pions. The possible existence of another boson at 3.4 GeV is also discussed.

Most of our present knowledge on the heavy bosons has been obtained from the missing-mass spectrometer experiments. The heaviest bosons so far reported using this technique lie in the neighborhood of 3 GeV.[1,2] The difficulties of this method are the large background, possible reflection of baryon resonances, and the fact that one often does not detect the decay products of the resonances observed.

Ever since the discovery of the ω meson in $\bar{p}p$ multipion annihilations it was thought that this reaction was best suited to search for high-mass bosons. The absence of nucleons in the final state increases the available energy for boson production and eliminates the background from reflections of baryon resonances. In the present paper we study the multipion $\bar{p}p$ annihilation events at an incident momentum of 6.94 GeV/c with the aim of looking for heavy bosons decaying into four and more pions. These decay modes may be expected for heavy bosons having large spin values, since angular momentum barriers would inhibit their decay into a few low-spin particles. In addition, bosons of positive G parity having an unnatural J^P value must decay into at least four pions.

In particular we report on the reactions

$$\bar{p}p \to 3\pi^+3\pi^- \text{ (117 events)}, \quad \sigma = 0.25 \pm 0.03 \text{ mb}, \quad (1)$$

$$\to 3\pi^+3\pi^-\pi^0 \text{ (735 events)}, \quad \sigma = 1.57 \pm 0.11 \text{ mb}, \quad (2)$$

identified in a sample of 25 000 pictures of the 80-in. Brookhaven National Laboratory hydrogen bubble chamber exposed to a 6.94-GeV/c separated $\bar{p}$ beam from the alternating-gradient synchrotron.

The six-prong events were measured on conventional measuring machines and processed through the geometrical-reconstruction and kinematic-constraints programs TVGP and SQUAW. Ionization estimates were used to resolve ambiguities with special attention to contamination from nucleon-antinucleon production and K^+K^- annihilation events. The experimental details and general features of these reactions have been described elsewhere.[3,4]

In Fig. 1(a) we show the neutral ($Q = 0$) six-pion