region, which should be investigated further. The lack of a significant enhancement in our total backward-hemisphere cross section argues against a $J \leq 2$ resonance interpretation of the data of Abrams et al. On the other hand, there appears to be a significant backward peak in our data which could be due to a resonance with $J = 3$-5.

We are indebted to Dr. F. Schweingruber for invaluable assistance with the antiproton beam, and to Dr. L. Voyvodic and the crew of the 30-in. bubble chamber at Argonne. Professor Tom Day was of great help in our initial use of the programs TVGP and SQUAW. Mr. M. Church made valuable programming contributions to the experiment. We appreciate the excellent work of our scanners and measurers. Finally we thank Professor D. Sinclair and Professor M. Ross for their suggestions and interest.

*Work supported by the U. S. Atomic Energy Commission.

†Address after 1 September 1968: Carnegie-Mellon University, Pittsburgh, Pa.

[1]B. Barish, D. Fong, R. Gomez, D. Hartill, J. Pine, A. V. Tollestrup, A. Maschke, and T. F. Zipf, Phys. Rev. Letters 17, 720 (1966).

[2]V. Domingo, G. P. Fisher, L. Marshall Libby, and R. Sears, Phys. Letters 24B, 642 (1967).

[3]G. R. Lynch, R. E. Foulks, G. R. Kalbfleisch, S. Limentani, J. B. Shafer, M. L. Stevenson, and N. H. Xuong, Phys. Rev. 131, 1276 (1963).

[4]W. A. Cooper, L. G. Hyman, W. Manner, B. Musgrave, and L. Voyvodic, Phys. Rev. Letters 20, 1059 (1968).

[5]R. J. Abrams, R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontić, K. K. Li, and D. N. Michael, Phys. Rev. Letters 18, 1209 (1967).

[6]G. Chikovani, L. Dubal, M. N. Focacci, W. Kienzle, B. Levrat, B. C. Maglić, M. Martin, C. Nef, P. Schubelin, and J. Seguinot, Phys. Letters 22, 233 (1966).

[7]See for example R. H. Dalitz, Ann. Rev. Nucl. Sci. 13, 339 (1963), especially p. 353 (Fig. 3).

[8]W. M. Katz, B. Forman, and T. Ferbel, Phys. Rev. Letters 19, 265 (1967).

[9]F. E. Hess, J. W. Chapman, J. Lys, C. T. Murphy, B. Roe, and D. Sinclair, Bull. Am. Phys. Soc. 13, 588 (1968).

[10]F. E. Hess, J. W. Chapman, J. Lys, C. T. Murphy, and J. C. Vander Velde, "Cross Sections for the Reactions $\bar{p}+p \to \pi^+ + \pi^-$ and $K^+ + K^-$ Near 2 GeV/c," to be published.

EVIDENCE FOR Ξ^* RESONANCE WITH MASS 1930 MeV*

J. Alitti, E. Flaminio, W. Metzger, D. Radojicic,‡ R. R. Rau, N. P. Samios, I. Skillicorn, and C. R. Richardson§
Brookhaven National Laboratory, Upton, New York

and

D. Bassano, M. Goldberg, and J. Leitner†
Syracuse University, Syracuse, New York

(Received 24 June 1968)

Evidence is presented for the existence of a baryon with a strangeness $S = -2$, mass $M = 1930 \pm 20$ MeV, and width $\Gamma = 80 \pm 40$ MeV. It is speculated that this resonance completes a $J^P = \frac{5}{2}^-$ octet. An SU(3) analysis of the conjectured $\frac{5}{2}^-$ octet gives a reasonable overall description of the partial widths of the member states.

In this Letter we present positive evidence for the existence of a Ξ^* resonance with mass $M = 1930$ MeV and width $\Gamma = 80$ MeV. The existence of such a state has been reported in two previous experiments.[1,2] The earlier data, although suggestive, were far from convincing because of limited statistics and difficulties with interference effects. The inconclusive nature of the old data is also indicated in the latest compilation by Rosenfeld et al.[3] To date, the confirmed baryon states with strangeness $S = -2$ are those with masses 1320, 1530, and with less confidence, 1815 MeV.[1,2,4] This is to be contrasted with the larger number of baryon states with $S = 0$ and $S = -1$. The difference is in part due to the ability to perform both formation and production experiments in the $S = 0, -1$ cases while only production experiments can be utilized to investigate $S = -2$ resonances. As a result, the number of established SU(3) baryon families is still limited to the $J^P = \frac{1}{2}^+$ octet and $\frac{3}{2}^+$ decuplet. At the conclusion of this Letter, we speculate on the possible existence of a second baryon octet with $J^P = \frac{5}{2}^-$.

The data for this report come from the continuing study of K^-p interactions at 3.9, 4.6, and 5.0 BeV/c momenta performed with the Brookhaven National Laboratory 80-in. hydrogen bubble chamber at the alternating gradient synchrotron. Combining the 4.6- and 5.0-BeV/c exposures, we have accumulated the equivalent of 18 events/μb cross section to date and 10 events/μb at 3.9 BeV/c. For this study, the final states of interest are

$\Xi^-\pi^+\pi^-K^+$, 238 events (4C); (1)

$\Xi^-\pi^+K^0$, 272 events (4C and 1C); (2)

$\Xi^-\pi^0K^+$, 130 events (1C); (3)

$\Xi^-\pi^+\pi^0K^0$, 178 events (1C); (4)

$\Sigma^0\bar{K}^0\pi^-K^+$, 33 events (2C); (5)

$\Lambda^0\bar{K}^0\pi^-K^+$, 138 events (4C). (6)

The nomenclature (1C), (2C), and (4C) indicates one-, two-, and four-constraint fits. The film has been scanned and measured for all events containing the visible decays of two strange particles. In Reactions (1) and (3) this involves the observation of both the Ξ^- and subsequent Λ^0 decay; in (2) the Ξ^- decay and either or both the Λ^0 or K^0 decay; in (4) the Ξ^- and K^0 decays with and without the Λ^0 decay; and in (5) and (6) both the $\bar{K}^0$ and Λ^0 decays. The events were analyzed using the BNL QLOD programming system supplemented by qualitative ionization information whenever required to resolve ambiguities. Only unique events, i.e., those with no other production fits with probability >1%, were retained in this search for $S=-2$ resonances. This procedure insured a pure sample of events[5] with a relatively small loss in statistics.

We present the evidence for $\Xi^*(1930)$ in two parts.

(a) First, we examine the $\Xi^-\pi^+$ effective-mass distribution from the four-constraint reaction (1) $\Xi^-\pi^+\pi^-K^+$ which contains 150 events at 4.6 BeV/c and 88 events at 3.9 BeV/c. This reaction is especially well suited in the search for $\Xi^{*0}\to\Xi^-\pi^+$ since this mass combination is free from any interference of known resonances. In Figs. 1(a) and 1(b) are plotted the $(\Xi\pi)$ effective mass for each energy respectively. The events with a recoiling $K^{*0}(890)\to K^+\pi^-$ are indicated in the crosshatched areas. The well-known $\Xi^*(1530)$ is clearly seen at both energies. In addition a three-standard-deviation effect at a $(\Xi\pi)$ mass of $M=1930\pm20$ MeV and width $\Gamma=80\pm40$ MeV is seen only in the data at 4.6 BeV/c. The indicated smooth curve in Fig. 1(a) is a combination of two Breit-Wigner shapes superimposed on a phase-space background.[6] The curve in Fig. 1(b) is that of a phase-space background with a single Breit-Wigner shape at the $\Xi^*(1530)$.[7] At the higher energy, the events with a recoiling K^{*0} also indicate an excess of events in the same $(\Xi\pi)$ mass region suggesting appreciable two-body production. The lack of a signal at 3.9 BeV/c may indeed be due to the reduction of the available phase space for $\Xi^*(1930)$ production in association with a $K^*(890)$. This cross section for $\Xi^*(1930)$ production is down a factor of at least 2 at 3.9 BeV/c compared with its value of 3 μb at 4.6 BeV/c.

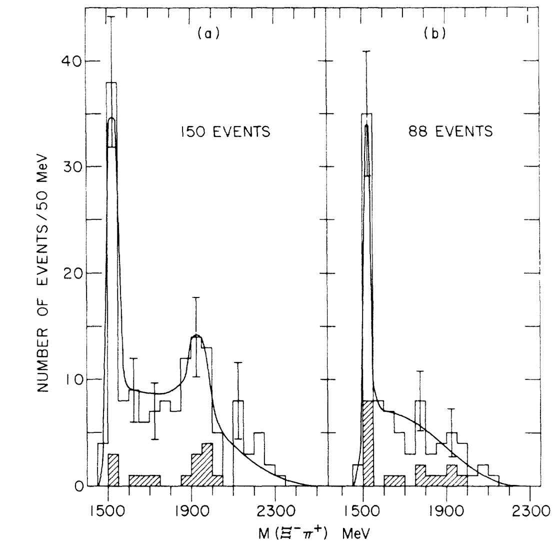

FIG. 1. The $(\Xi^-\pi^+)$ mass distribution from the reaction $\Xi^-\pi^+K^+\pi^-$. Incident K^- momenta (a) 4.6 and 5.0 BeV/c and (b) 3.9 BeV/c. Events with $K^*(890)\to K^+\pi^-$ are indicated by cross-hatching.

(b) Second, we study the $(\Xi\pi)$ effective mass distribution from Reactions (1)-(4), namely all three- and four-body Ξ^- production channels. However, the latter three final states must be handled carefully because of the possible reflections of known resonances, namely $K^*(890)$. The procedures adopted in the case of Reactions (2) and (3) are to remove the peripherally produced K^* events [i.e., $\Delta^2_{KK^*}<1.2$ (BeV/c)^2]; while in (4) the K^{*+} [defined by 860 MeV$<M(K^*)<920$ MeV] was removed before plotting the $\Xi^-\pi^+$ effective mass and the K^{*0} (similarly defined as the K^{*+}) was removed in the case of $\Xi^-\pi^0$ effective mass. The resultant $(\Xi^-\pi)$ mass distributions for the two incoming energies are shown in Figs. 2(a) and 2(b). Once again the $\Xi^*(1530)$ is

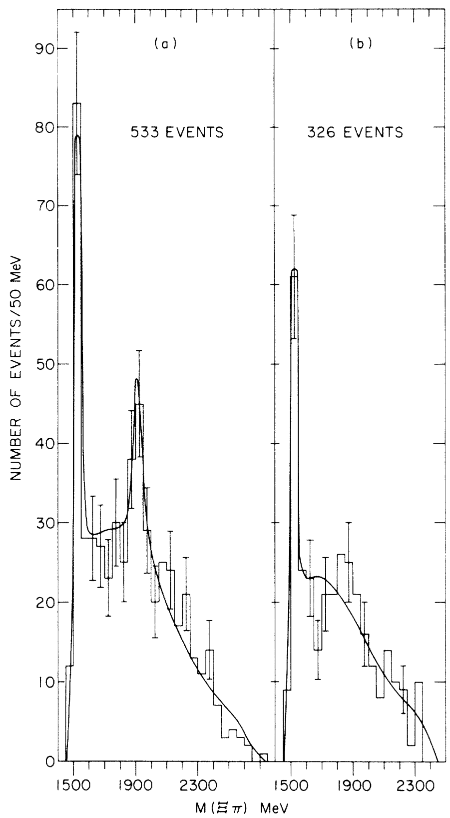

FIG. 2. The $(\Xi^-\pi^+)$ and $(\Xi^-\pi^0)$ mass distribution from three- and four-body reactions. See discussion in text. Incident K^- momenta (a) 4.6 and 5.0 BeV/c and (b) 3.9 BeV/c.

clearly seen at both energies as well as a three-standard-deviation effect at a mass $M = 1920 \pm 15$ MeV and width $\Gamma = 80 \pm 40$ MeV, but only at the 4.6-BeV/c energy. The indicated smooth curves are a combination of expected phase space distribution with appropriate Breit-Wigner curves.[8] It should be noted that the main contribution to the $\Xi^*(1930)$ peak comes from Reaction (1), the other channels serving to increase the signal from 19 to 27 events and to smooth out the background. In particular, the $(\Xi^-\pi^0)$ mass combination shows a reduced $\Xi^*(1530)$ signal and no excess of events at a mass of 1930. Furthermore, we see no effect in the $(\Xi^-\pi^-)$ mass combination in Reaction (1). Both these observations indicate that the isospin, I, of the $\Xi^*(1930)$ is $I = \frac{1}{2}$.

We now turn to a discussion of the possible existence of another SU(3) baryon octet with spin and parity $J^P = \frac{5}{2}^-$, similar to those given by Goldberg et al. and Tripp et al.[9] To date there are three known resonances with this spin and parity,[3] namely a nucleon with isospin $I = \frac{1}{2}$, strangeness $S = 0$, and mass 1680 MeV; a Λ baryon with $I = 0$, $S = -1$, and mass 1827 MeV; and finally a Σ baryon $I = 1$, $S = -1$, and mass 1767 MeV. On the assumption that these states are part of an octet, the Gell-Mann–Okubo mass formula predicts a Ξ baryon with $I = \frac{1}{2}$, $S = -2$ at a mass of 1944 MeV. This prediction agrees quite well with the mass of the resonance observed in this experiment, making it therefore a prime candidate for completing the octet. Further, it is of interest to compare the observed decay rates with those predicted by SU(3).[9] The known decay modes and measured partial widths are shown in Table I. The SU(3) couplings for each mode are also given in terms of the parameter α which measures the mixture of D (symmetrical) and F (antisymmetrical) couplings.[10] In our convention pure D corresponds to $\alpha = 0$ and pure F to $\alpha = 1$. The decay rates are assumed to be given by the expression

$$\Gamma = C^2 |M|^2 B_l(p)(p/\lambda),$$

where C = SU(3) Clebsch-Gordan coefficient, M = the effective matrix element, B_l = the barrier penetration factor for a given angular momentum[11] l, and p/λ = the phase-space factor, where p is the center-of-mass momentum of one of the decay particles and λ is the mass of the resonance. The Clebsch-Gordan coefficients for the decay modes of interest are shown in Table I. There are two unknown parameters to be determined, α and $|M|^2$.[12] We have used the branching ratio of the Σ decay to fix α and the decay rates for the two baryons, N and Σ, to arrive at a best value for $|M|^2$. The result is $\alpha = -0.12$, i.e., mainly D coupling. With these values, one can then predict the $\Xi^*(1930)$ total and partial widths as well as those derived for the other final states of the octet. The resultant partial widths are shown in Table I. The predicted $\Xi^*(1930)$ width is ≈ 70 MeV in excellent agreement with our measured value of 80 ± 40 MeV. The predicted partial width for $N \to N\pi$ is 40 MeV which is in good agreement with the experimental value of 54 ± 24.[3] Similarly the mode $\Lambda \to \Sigma\pi$ is predicted to have a partial width of 50 MeV to be compared with the reported value of 33 MeV. However this state has complications due to its proximity to the $J^P = \frac{5}{2}^+$, $\Lambda(1815)$ resonance[13] so that its branching ratio into $\Sigma\pi$ is certainly subject to a large uncertainty. In order to make an experimental comparison for the various Ξ decay modes we restrict ourselves to Reaction (1), where the signal is clear, and to Reactions (5) and (6). From the unique sample of 155 $\Lambda^0\bar{K}^0K^+\pi^-$

Table I. Tabulation of the experimental and SU(3) predicted partial widths for the various decay modes of the postulated members of the $J^P = \frac{5}{2}^-$ octet.

	Mass (MeV)	total (MeV)	Decay Modes	Branching Ratio (%)	Partial Width Experimental (MeV)	SU(3) Clebsch-Gordon Coefficient	Partial Width Predicted (MeV)
N	1680	135	$N\pi$	40	54	3	40
Λ	1827	76	$N\bar{K}$	8	6	$2/3(1+2\alpha)^2$	4
			$\Sigma\pi$	42	32	$4(1-\alpha)^2$	50
Σ	1767	95	$N\bar{K}$	46	44	$2(1-2\alpha)^2$	31
			$\Lambda\pi$	15	14	$4/3(1-\alpha)^2$	18
			$\Sigma\pi$	1	1	$8\alpha^2$	1
Ξ	1930	80	$\Xi\pi$	Observed		$3(1-2\alpha)^2$	41
			$\Sigma\bar{K}$	(Not Observed < 70)		3	20
			$\Lambda\bar{K}$	(Not Observed < 30)		$1/3(4\alpha-1)^2$	7

and 33 $\Sigma^0\bar{K}^0K^+\pi^-$ events we see no evidence for the $\Xi^*(1930)\rightarrow\Lambda\bar{K}^0$ or $\Sigma^0\bar{K}^0$. However this is still consistent with the SU(3) prediction since the expected number in each channel $\Xi^-\pi^+:\Sigma^0\bar{K}^0:\Lambda^0\bar{K}^0$ is expected to be in the ratio 12:1:1 for an $I=\frac{1}{2}$ Ξ state.[14]

We therefore conclude that the new evidence presented here indicates the existence of a Ξ resonance at mass $M = 1930$ MeV. An application of the Gell-Mann–Okubo mass formula suggests that it is a member of a $J^P = \frac{5}{2}^-$ baryon octet and detailed SU(3) study of the total and partial widths of the member states seems to give a reasonable overall consistent picture.

We wish to acknowledge the aid of the AGS and 80-in. bubble-chamber staffs and crews in obtaining the pictures, the efforts of our data analysis personnel in processing all the pictures and events, and the support of Dr. R. P. Shutt throughout the progress of the experiment.

---

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

‡Present address: Oxford University.

†Deceased.

§Present address: U. S. Atomic Energy Commission, Washington, D. C.

[1]J. Badier et al., Phys. Letters 16, 171 (1965).

[2]G. A. Smith and J. S. Lindsey, in Proceedings of the Athens Second Topical Conference on Resonant Particles, edited by B. A. Munir (Ohio University Press, Athens, Ohio, 1965), p. 251.

[3]A. H. Rosenfeld et al., University of California Radiation Laboratory Report No. UCRL-8030, Rev., 1968 (unpublished).

[4]G. A. Smith et al., Phys. Rev. Letters 14, 25 (1965). This includes earlier references.

[5]In Reactions (2) and (4) a comparison of events with both Λ^0 and K^0 decays seen with those events where only the K^0 decays essentially agreed with that expected from known branching ratios and indicates that less than 10% of the events are lost by omitting the ambiguous events.

[6]A χ^2 fit to all the data of Fig. 1(a) with the higher mass Breit-Wigner removed gave a goodness-of-fit probability $\approx 1\%$.

[7]A single resonance hypothesis with one Breit-Wigner at 1530 MeV gave a χ^2 probability of 75%.

[8]In the case of 4.6-BeV/c data, the χ^2 fit with phase space of one Breit-Wigner at 1530 gave a 5% probability to be contrasted to a 50% probability for phase space and two Breit-Wigners (1530 and 1920 MeV). The data at 3.9 BeV/c gave 8% and 9% for the same two respective cases.

[9]M. Goldberg et al., Nuovo Cimento 45A, 169 (1966); R. D. Tripp et al., Nucl. Phys. B3, 10 (1967).

[10]In our convention $\alpha^{-1} = 1 + 3g_d/5^{1/2}g_f$, where g_d and g_f are the symmetrical and antisymmetrical couplings of two SU(3) octets. This is to be contrasted to the convention used by Tripp et al., Ref. 9, which is $\alpha^{-1} = 1 + 5^{1/2}g_f/3g_d$.

[11]The barrier penetration factor used is that given by J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics, (John Wiley & Sons, New York, 1952), p. 361.

[12]The radius of interaction is also a variable. However the results are insensitive to both the value of this radius as well as the explicit form used for the barrier penetration factor. The value used for the radius in this calculation was 1 F.

[13]R. Armenteros et al., Phys. Letters 24B, 198 (1967).

[14]From a consideration of isospin and corrections for neutral decay modes, one obtains $\Xi^-\pi^+:\Sigma^0\overline{K}^0:\Lambda^0\overline{K}^0=6:1:3$. The additional factors come from the SU(3) Clebsch-Gordan coefficients with $\alpha=0.12$.

STUDY OF $Y_1^*(1660)^\pm \to \Sigma^0\pi^\pm$ (AND $\Lambda\pi^\pm$)*

J. Button-Shafer
Lawrence Radiation Laboratory, University of California, Berkeley, California,
and University of Massachusetts, Amherst, Massachusetts
(Received 11 July 1968)

Large samples of $Y^*(1660)^\pm \to \Sigma^0\pi^\pm$ have been analyzed. Little $\Lambda\pi$ decay is observed, but $\Sigma\pi$ and $Y_0^*(1405)\pi$ modes are comparable. The spin and parity conclusion from $\Sigma^0\pi$ study is $\frac{3}{2}^-$.

Many conflicting results have been obtained for the decay branching ratios and the spin and parity assignment of the $Y_1^*(1660)$. First indications of its existence, its spin, and its SU(3) classification were all presented in three simultaneous reports made about five years ago[1]; however, subsequent studies yielded very confusing results.[2]

The inconsistencies were partially resolved recently when three separate analyses demonstrated the existence of a new $Y_1^*(1695)$ decaying predominantly into $\Lambda\pi$.[3,4] The report of Primer et al. shows [from inspection of about 250 $\Sigma^0\pi^+\pi^-$, 800 $\Lambda\pi^+\pi^-$, and 180 $Y_0^*(1405)\pi^+\pi^-$ events] that the $Y_1^*(1660)$ has branching ratios of about 60% into $\Sigma\pi$ and 40% into $Y_0^*(1405)\pi$, whereas the $Y_1^*(1695)$ decays predominantly into $\Lambda\pi$.[4]

This article presents information on K^- interactions at 1.7 BeV/c:

$$K^- + p \to \Sigma^0 + \pi^+ + \pi^- \text{ (990 events)}, \quad (1)$$

$$K^- + p \to \Lambda + \pi^+ + \pi^- \text{ (1538 events)}. \quad (2)$$

Data on $\Sigma^0\pi^+\pi^-$(1346 events) at 2.1 BeV/c are also discussed.

At 1.7 BeV/c a strong $Y_1^*(1660)$ enhancement exists in both the $\Sigma^0\pi^+$ and $\Sigma^0\pi^-$ systems in Reaction (1); a questionable peak is seen near 1660 MeV in the $\Lambda\pi^+$ system of Reaction (2). The $\Lambda\pi$ spectra show no evidence of $Y_1^*(1695)$ production.

Comparison is made of the $\Sigma^0\pi$ data at 2.1 BeV/c with published results on $Y_0^*(1405)\pi$ at this momentum.[5] The branching ratios obtained are in agreement with those of Ref. 4.

Spin and parity analysis of the decay sequence $Y_1^*(1660) \to \Sigma^0\pi$, $\Sigma^0 \to \Lambda + \gamma$, and $\Lambda \to p + \pi^-$ yields a $\frac{3}{2}^-$ assignment, in support of the conclusion of Eberhard, Pripstein, and Shively from $Y_1^*(1660) \to Y_0^*\pi$.[5] This lends further validity to the Primer et al. designation of $\Sigma\pi$ as a significant decay mode of the $Y_1^*(1660)$. (Alternatively, this study supports positive Σ^0 parity.)

In 1965 realignment of the "K-63" beam channel at the Bevatron was carried out in collaboration with Joseph J. Murray to obtain a 1.7-BeV/c K^- beam and an exposure of 3500 events/mb in the 72-in. bubble chamber. The primary purpose was to obtain a relatively clean, large sample of events containing the $Y^*(1660)$ as a final-state resonance of $\Sigma^0\pi$. The earlier "K-72" data (1.2-1.7 BeV/c) had yielded a very impressive peak near 1660 MeV in the $\Sigma^0\pi^+$ mass spectrum[6]; however, spin and parity analysis produced inconclusive results.

The "K-63" film yielded some 990 events fitting Reaction (1) rather well; i.e., the confidence level for this hypothesis was ≥ 0.005 and was at least three times greater than that for any competing hypothesis ($\Lambda\pi^+\pi^-$ or $\Lambda\pi^+\pi^-\pi^0$). However, to obtain a very pure sample of $\Sigma^0\pi^+\pi^-$ the author imposed more stringent conditions, namely, that the confidence level be ≥ 0.20. (The distribution in the $\Sigma^0\pi\pi$ confidence level showed considerable peaking below about 0.10, but was flat above 0.20.) To check possible bias, spin and parity analysis was carried out with a confidence-level minimum of 0.05; parameters obtained were quite similar to those found with a minimum of 0.20.

The number of events at 1.7 BeV/c which fitted $\Sigma^0\pi^+\pi^-$ production with a confidence level ≥ 0.20 was 613. Figure 1 shows the Dalitz plot and mass projections. The $Y^*(1660)^\pm$ resonance bands overlap near the center of the Dalitz plot. It would have been difficult to describe the production mechanism at 1.7 BeV/c completely. Therefore the $Y^*(1660)^-$ resonant band, as well