

PRODUCTION OF $p\pi^+\pi^-$ ENHANCEMENTS FROM THE REACTION $K^-p \rightarrow K^-p\pi^+\pi^-$
AT 3.9, 4.6, AND 7.3 GeV/c*

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Evidence is presented for the existence of an $N^*(1710)$ ($M = 1712 \pm 6$ MeV and $\Gamma = 70 \pm 15$ MeV) produced in the reaction $K^-p \rightarrow K^-p\pi^+\pi^-$ at incident momenta of 3.9, 4.6, and 7.3 GeV/c. It decays mainly into $p\pi^+\pi^-$ and not through the $\Delta^{++}\pi^-$ intermediate state, with some indication for a ΛK^+ decay mode. Also observed in the $p\pi^+\pi^-$ invariant mass spectrum is the $N^*(1470)$.

In the past five years, there have been numerous production-experiment investigations¹ into the low-energy region of the $N\pi\pi$ mass spectrum. Most of these experiments agree in that they find an enhancement at 1470 MeV, just above the $\Delta(1238)\pi$ threshold. However the situation is more complicated in the 1650-1750 mass region, with reports of peaks at different masses and with widths varying from 50 to 150 MeV. Detailed phase-shift analyses of the pion-nucleon system also suggest the existence of many resonances in this same mass region, all of which have widths between 125 and 400 MeV. In this Letter we report the observation of a $p\pi^+\pi^-$ resonance at a mass of 1710 MeV and with a width of 70 MeV produced in the reaction $K^-p \rightarrow K^-N^*(1710)$ at 3.9, 4.6, and 7.3 GeV/c incident momenta. This is the first high-statistics experiment to observe a narrow peak at this mass produced in K^-p interactions. The $N^*(1710)$ is found to decay into an uncorrelated $p\pi\pi$ final state and not through the $\Delta^{++}\pi^-$ or $\Delta^0\pi^+$ intermediate states. The possible existence of a ΛK decay mode as well as similar production cross sections for the $N^*(1710)$ at 3.9-4.6 and 7.3 GeV/c suggests isospin $\frac{1}{2}$.

The data presented here come from three exposures of the Brookhaven National Laboratory 80-in. hydrogen bubble chamber at 3.9, 4.6, and 7.3 GeV/c incident momenta. The reaction of interest is



From a total of 62 000 measured four-pronged events at 3.9 and 4.6 GeV/c incident momenta and 20 000 measurements at 7.3 GeV/c, the subsamples of 13 847 and 3865 events, respectively, fit reaction (1) (four-constraint hypothesis) with a chi-squared probability greater than 1%, and have ionization (as measured by the Brookhaven National Laboratory flying-spot digitizer) consistent with the kinematic identification. This sample corresponds to 9.7 events/ μb at 3.9-4.6

GeV/c and 4.6 events/ μb at 7.3 GeV/c. Since, within statistics, the data at 4.6 and 3.9 GeV/c do not exhibit any significant differences important for this investigation, we henceforth treat them as a unit.

For the remainder of this analysis we have removed the well-defined $K^*(890)$ events.² The resultant $p\pi^+\pi^-$ spectrum at 7.3 GeV/c is shown in Fig. 1(a). There is clear evidence for an $N^*(1710)$, a 4-5 standard-deviation peak, as well as for an enhancement centered at about 1470 MeV. The fact that both effects are peripherally produced is indicated in Fig. 1(b), which contains only those events whose production-angle cosine (the production angle is that between the incoming and outgoing kaons in the total center-of-mass system) $\cos\theta^*$ is greater than 0.9. Both peaks appear prominently above a reduced background. The $p\pi^+\pi^-$ invariant mass distribution for the 3.9-4.6 GeV/c sample is displayed in Fig. 1(c). A 5-6 standard-deviation signal from the $N^*(1710)$ is observed as well as an excess of events in the low-energy region. Figure 1(d) is the $p\pi^+\pi^-$ spectrum from this latter sample with $\cos\theta^* > 0.9$. This selection substantially increases the signal-to-background ratio of the $N^*(1710)$ and shows the low-mass enhancement as a greater than 4 standard-deviation effect. In order to determine the masses and widths of these enhancements, we have used the 7.3 GeV/c data with no $\cos\theta^*$ selection and the 3.9-4.6 GeV/c data with $\cos\theta^* > 0.9$.³ Two S-wave Breit-Wigner shapes and a smooth hand-drawn background have been fitted [curves in Figs. 1(a) and 1(d)]. For the low-mass peak we obtain⁴

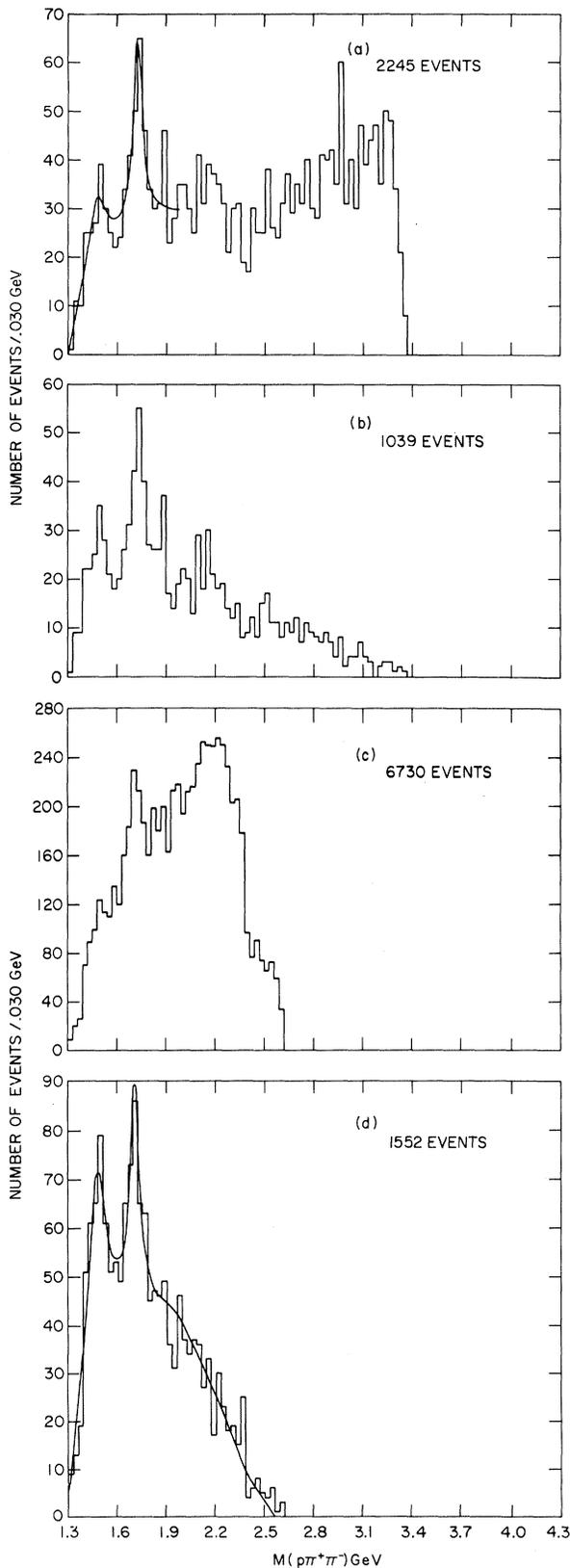
$$M = (1466 \pm 15) \text{ MeV}, \quad \Gamma = (130 \pm 30) \text{ MeV}$$

at 7.3 GeV/c;

$$M = (1479 \pm 11) \text{ MeV}, \quad \Gamma = (110 \pm 26) \text{ MeV}$$

at 3.9-4.6 GeV/c. The results for the $N^*(1710)$,

$$M = (1720 \pm 10) \text{ MeV}, \quad \Gamma = (75 \pm 20) \text{ MeV}$$



at 7.3 GeV/c,

$$M = (1707 \pm 8) \text{ MeV}, \quad \Gamma = (65 \pm 20) \text{ MeV}$$

at 3.9-4.6 GeV/c, are in good agreement with each other, yielding weighted-average values $M = 1712 \pm 6$ MeV and $\Gamma = 70 \pm 15$ MeV. As a test that our geometry-kinematic fitting programs do not give rise to any systematic effects, we have determined the mass and width of the $K^*(890)$ from Reaction (1). We find

$$M = (895 \pm 1) \text{ MeV}, \quad \Gamma = (51 \pm 2) \text{ MeV}$$

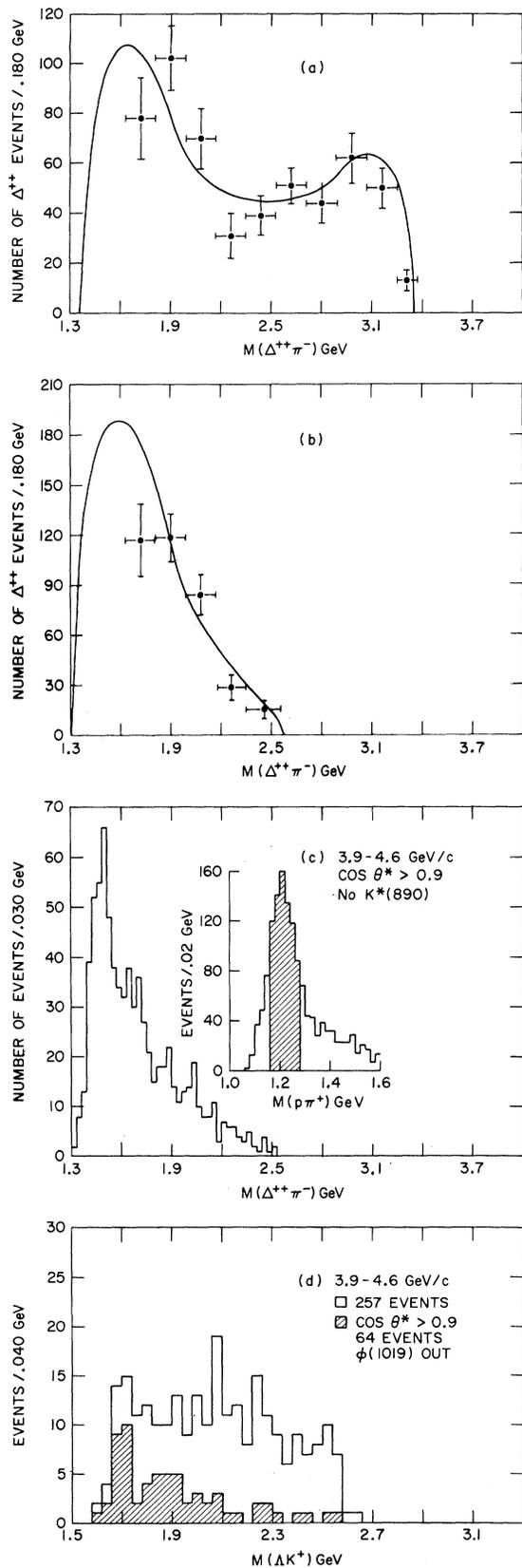
at 7.3 GeV/c,

$$M = (894.6 \pm 0.5) \text{ MeV}, \quad \Gamma = (50 \pm 1.5) \text{ MeV}$$

at 3.9-4.6 GeV/c, in excellent agreement with each other and with the world averages. Furthermore the resolution of the $p\pi\pi$ mass in the 1710 region is calculated to be less than 10 MeV. We note that the value for the mass of this $p\pi\pi$ enhancement is higher than that of the well-known $N(1688)$ with $J^P = \frac{5}{2}^+$ and its width is ~50% smaller than that reported, i.e., 70 versus 125 MeV. Most other production experiments¹ also tend to have masses above 1690 MeV and widths smaller than 100 MeV, in agreement with our data.

We now turn to a study of whether the $N^*(1710)$ decays into $\Delta(1238)\pi$. For this purpose a $\cos\theta^* > 0.9$ selection was imposed on the 3.9-4.6 data and no cut was required in the 7.3 GeV/c case. Due to the limited Q value for the $\Delta\pi$ decay channel, the simple procedure of examining the $p\pi^\pm$ mass projection is not very fruitful since it is difficult to differentiate between actual $\Delta(1238)$ signal and phase space. The approach we have adopted instead is to fit the $p\pi^+\pi^-$ Dalitz plot using the following method. For a series of 0.18 GeV intervals encompassing the $N^*(1710)$ and higher $p\pi^+\pi^-$ masses, we determine by the maximum-likelihood method⁵ two parameters, ϵ and α , where ϵ is the fraction of Δ^{++} events and α is the parameter⁶ needed to describe the Δ^{++} decay

FIG. 1. (a) The $p\pi^+\pi^-$ invariant-mass spectrum from the reaction $K^- p \rightarrow K^- p\pi^+\pi^-$ at 7.3 GeV/c. Events with $820 \text{ MeV} < M(K^-\pi^+) < 980 \text{ MeV}$ have been removed. The curve shows a fit of two S-wave Breit-Wigner shapes and a hand-drawn background. (b) Same as (a) but for events with $\cos\theta^* > 0.9$. (c) Same as (a) but for the 3.9-4.6 GeV/c sample. (d) Same as (c) but for events with $\cos\theta^* > 0.9$. The curve shows a fit of two S-wave Breit-Wigner shapes and a hand-drawn background.



angular distribution. The following form for the square of the amplitude for the $p\pi^+\pi^-$ state was used⁷:

$$|m|^2 = \epsilon \frac{|m_\Delta|^2}{\sum \int |m_\Delta|^2 d\varphi} + \frac{1-\epsilon}{\sum \int d\varphi}, \quad (2)$$

where $\sum \int d\varphi$ signifies integration over the $p\pi^+\pi^-$ Dalitz plot plus the sum over events in a given $p\pi^+\pi^-$ mass interval. $|m_\Delta|^2$ is the square of the amplitude for Δ^{++} intermediate state given by

$$|m_\Delta|^2 = |f_{BW}(M, \Gamma)|^2 [(1+a) + 3(1-a)\cos^2\theta]/4, \quad (3)$$

where $f_{BW}(M, \Gamma)$ is the standard Breit-Wigner function for the Δ^{++} resonance,⁸ M is the $p\pi^+$ effective mass, and θ is the angle between π^- and proton in the Δ^{++} rest system. Parameters ϵ and a are restricted to be in the following ranges: $0 \leq \epsilon \leq 1$ and $0 \leq a \leq 2$. The estimated numbers of Δ^{++} events calculated from ϵ are shown in Fig. 1(a) [2(b)] for the 7.3 (3.9-4.6) GeV/c sample. The most striking feature is the lack of a surplus of Δ^{++} events in the $N^*(1710)$ region. In fact the number of Δ^{++} events in the $N^*(1710)$ interval is less than the number in the adjacent $\Delta^{++}\pi^-$ mass interval and less than the background prediction [solid curve⁹ in Figs. 2(a) and 2(b)] of a double-Regge-pole model. Thus, our data clearly suggest that all the Δ^{++} events in the $N^*(1710)$ interval come from the background and not from the $N^*(1710)$ resonance.¹⁰ Further substantiating this conclusion is the fact that when, for the 3.9-4.6 GeV/c data, a narrow Δ^{++} slice [shown as an insert in Fig. 2(c)], $1.16 \leq M(p\pi^+) \leq 1.28$ GeV, is required, the resultant ($\cos\theta^* > 0.9$) $\Delta^{++}\pi^-$ spectrum [Fig. 2(c)] exhibits little if any $N^*(1710)$ signal.¹¹

We now turn to a discussion of possible alternate decay modes¹² and the isospin of the $N(1710)$. The existence of a ΛK mode ($I = \frac{1}{2}$) was searched for in the reaction $K^-p \rightarrow \Lambda K^+ K^-$ at 3.9-4.6 GeV/c [see Fig. 2(d)], and after removal of the $\phi(1019)$

FIG. 2. (a) The estimated number of Δ^{++} events in 0.18 GeV intervals of $p\pi^+\pi^-$ mass (see text) for the 7.3 GeV/c sample. The curve indicates the prediction of the double Regge-pole model normalized to the number of Δ^{++} events with $M(\Delta\pi) > 1.81$ GeV. (b) Same as (a) but for the 3.9-4.6 GeV/c sample. (c) The $\Delta^{++}\pi^-$ mass spectrum ($\cos\theta^* > 0.9$) for a narrow Δ^{++} selection [$1.16 < M(p\pi^+) < 1.28$ GeV]. The insert shows the $p\pi^+$ mass spectrum with the Δ^{++} band shaded. (d) Invariant-mass spectrum for ΛK^+ from the reaction $K^-p \rightarrow \Lambda K^+ K^-$. Events with $\cos\theta^* > 0.9$ are shown shaded.

events, a signal of 16 ± 7 events (corresponding to $1.9 \pm 0.9 \mu\text{b}$) was found at a mass of approximately 1700 MeV.¹³ The shaded portion of Fig. 2(d) shows the $M(\Lambda K^+)$ spectrum with a $\cos\theta^* > 0.9$ selection. A clear signal is now apparent with mass and width consistent with the values obtained for the $p\pi^+\pi^-$ enhancement at 1710 MeV. Taking events with a $\cos\theta^* > 0.9$ selection, we find a branching ratio

$$(4 \pm 1.5)\% < \frac{\Lambda K}{\text{all } N\pi\pi} < (8 \pm 3)\%,$$

where the lower (upper) limit corresponds to the $\pi\pi$ system in a pure $I=1$ ($I=0$) state. Further evidence favoring isospin $\frac{1}{2}$ comes from the observation of equal production cross sections for the $N^*(1710)$ at 7.3 and 3.9-4.6 GeV/c.¹⁴

It is difficult to determine the spin and parity of the $N^*(1710)$ due to the presence of a large background amounting to more than half the events in the resonant region. Thus we can only give consistency arguments for a given spin state. In the analysis, a $\cos\theta^* > 0.9$ selection was imposed and the events were combined at the two energies; the 3.9-4.6 and 7.3 GeV/c data were examined separately and found to contain no significant differences. A few of the relevant angular distributions are displayed in Fig. 3 for both the $N^*(1710)$ and the background regions.¹⁵ These angles¹⁶ are defined in the figure captions. Taking into account the background, the angular distributions for the $N^*(1710)$ resonant events are all compatible with being isotropic, which is consistent with a spin- $\frac{1}{2}$ hypothesis, but does not rule out higher spins.

In summary, we conclude that in our data we observe two $p\pi\pi$ resonances, one centered near 1470 MeV and the other at 1710 MeV. The former is most likely the well-known Roper resonance. If the $N^*(1710)$ is identified with the $N(1688)$, then we observe a higher mass and narrower width than those derived from phase-shift analyses. However the suggested spin and isospin of the $N^*(1710)$ seen in this experiment are consistent with the $S_{11}(1710)$ or the $P_{11}(1750)$ resonances reported in πN phase-shift analyses. There is disagreement between the widths, 70 versus >200 MeV; however, this may not be a serious discrepancy, considering the difficulty of determining resonance widths in phase-shift analyses. The $N^*(1710)$ is observed to decay via $p\pi\pi$ and not $\Delta\pi$. Indications of a ΛK decay rate larger than the upper limit quoted for the $N(1688)$,¹⁷ in addition to the observed mass and width, argue

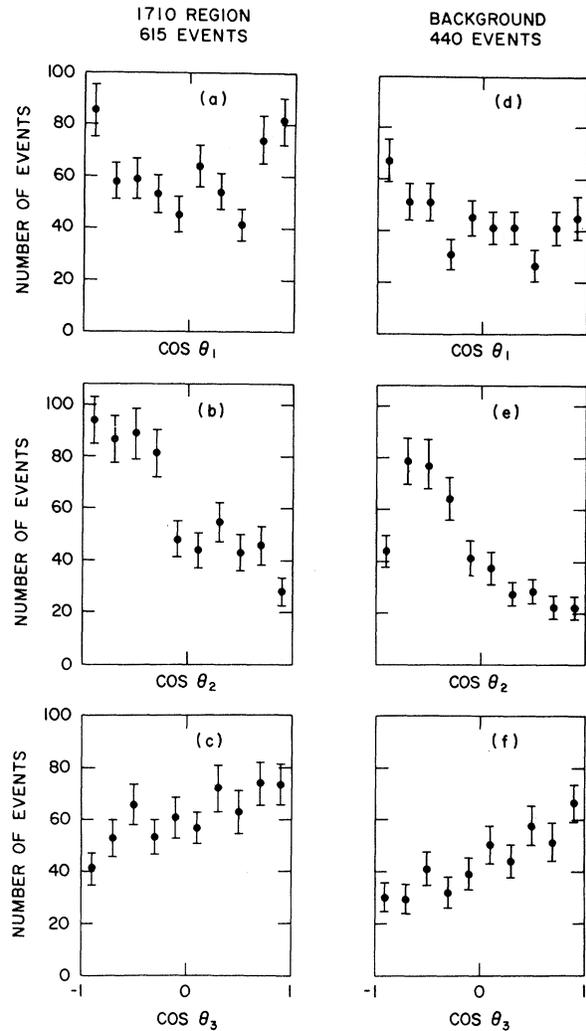


FIG. 3. (a) $\text{Cos}\theta_1$, where (in the $p\pi^+\pi^-$ rest frame) θ_1 is the angle between the normal to the production plane and the normal to the decay plane, for events with $p\pi^+\pi^-$ mass in the 1710 region. (b) $\text{Cos}\theta_2$, where (in the $\pi^+\pi^-$ rest frame) θ_2 is the angle between the π^- and the final proton, for events with $p\pi^+\pi^-$ mass in the 1710 region. (c) $\text{Cos}\theta_3$ is the same as $\text{cos}\theta_2$ but in the $p\pi^+$ rest frame. (d), (e), (f) The same as (a), (b), and (c), respectively, but for events with $p\pi^+\pi^-$ mass in the background regions. The $N^*(1710)$ region is defined as $1.63 \leq M(p\pi^+\pi^-) \leq 1.81$ GeV. The background regions are $1.52 \leq M(p\pi^+\pi^-) \leq 1.63$ GeV and $1.81 \leq M(p\pi^+\pi^-) \leq 1.90$ GeV.

against the association of the $N^*(1710)$ and the $N(1688)$.

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¹The low mass 1470 enhancement has been observed in other experiments as reported by J. G. Rushbrooke, 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. 158. A summary of enhancements in the 1700 region is also given in this reference; see also V. Alles-Borelli *et al.*, Nuovo Cimento **47A**, 232 (1967); R. Ehrlich *et al.*, Phys. Rev. Letters **21**, 1839 (1968); J. Ballam *et al.*, Presented to the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September 1968 (unpublished); K. F. Galloway *et al.*, Phys. Letters **27B**, 250 (1968).

²The $K^*(890)$ band is taken to be $820 \text{ MeV} \leq M(K^-\pi^+) \leq 980 \text{ MeV}$.

³We obtain comparable values for the mass and width of the $N^*(1710)$ by fitting the 3.9–4.6 GeV/c data without the $\cos^*\theta$ cut.

⁴The lower-mass enhancement occurs on a rapidly rising background so that the determination of its mass and width is subject to some uncertainty in addition to the statistical errors quoted.

⁵By using the program MINFUN, we have maximized the following likelihood function: $\mathcal{L} = \prod_k \{ |m|^2 / \int |m|^2 d\varphi \}_k$, where the product is over the events in a given $M(p\pi^+\pi^-)$ interval and $d\varphi$ is the differential element of area on the $p\pi^+\pi^-$ Dalitz plot of the k th event.

⁶The parameter a is related to the ratio of the square of helicity amplitudes $|g_{3/2}|^2$ and $|g_{1/2}|^2$ [with the normalization $2|g_{3/2}|^2 + 2|g_{1/2}|^2 = 1$: $|g_{3/2}|^2 / |g_{1/2}|^2 = a / (2 - a)$].

⁷A more general form of the amplitude would have to include a term corresponding to the Δ^0 intermediate state. However, for both energies it was not necessary to include this term in our analysis due to the negligibly small fraction of Δ^0 events.

⁸The precise form of the Breit-Wigner function we

have used is as follows

$$|f_{\text{BW}}(M, \Gamma)|^2 = \frac{M}{q} \frac{\Gamma(q/q_0)^3}{(M^2 - M_0^2)^2 + (M_0\Gamma)^2(q/q_0)^6},$$

where M_0 and Γ are the mass and width of Δ and q (q_0) is the breakup momentum of the $p\pi$ system with effective mass M (M_0).

⁹The double Regge-pole theoretical distributions have been normalized to the number of events with $M(\Delta^+\pi^-) > 1.81 \text{ GeV}$. We have used a double Regge-pole model with an incoherent superposition of (ρ, π) and (K^*, π) exchange. The details of the calculation will be presented in a future publication.

¹⁰If we take the number of $\Delta^+\pi^-$ events in the $\Delta^+\pi^-$ background under the $N^*(1710)$ to be equal to the number of $\Delta^+\pi^-$ in the neighboring region ($1.81 \text{ GeV} < M(p\pi^+\pi^-) < 1.99 \text{ GeV}$), we find -25 ± 20 resonant $\Delta^+\pi^-$ events in the 7.3 GeV/c data and -2 ± 27 at 3.9–4.6 GeV/c. From this we obtain a 2 standard-deviation upper limit of 15% for the $\Delta^+\pi^- / p\pi^+\pi^-$ branching ratio.

¹¹Bands on both sides of the Δ^+ slice show as much $N^*(1710)$ in their $(p\pi^+)\pi^-$ spectra as does the central Δ^+ region. This indicates that the peaking in the $\Delta^+\pi^-$ mass spectrum at 1710 MeV is not associated with real Δ^+ events. A similar conclusion is reached for the 7.3 GeV/c data.

¹²The possible decay of the $N^*(1710)$ into $N\pi$ will be investigated via the reactions $K^-p \rightarrow K^-p\pi^0$ and $K^-p \rightarrow K^-n\pi^+$. However the $F_{15}(1688)$, $S_{11}(1710)$, and $P_{11}(1750)$, all of which can be associated with the observed $N^*(1710)$, have large but poorly known $N\pi$ decay modes. Therefore such a measurement may not completely resolve this problem.

¹³D. Crennell, K. W. Lai, J. Scarr, and T. Schumann, Phys. Rev. Letters **19**, 1212 (1967), have observed a ΔK enhancement in this mass region produced in pion-nucleon interactions.

¹⁴The production cross section for the $N^*(1710) \rightarrow p\pi^+\pi^-$ is $27 \pm 6 \mu\text{b}$ at 3.9–4.6 GeV/c and $24 \pm 6 \mu\text{b}$ at 7.3 GeV/c. This suggests production via Pomeranchukon exchange, which would require $I = \frac{1}{2}$ for the $N^*(1710)$.

¹⁵The $N^*(1710)$ band is defined as $1.63 \leq M(p\pi^+\pi^-) \leq 1.81 \text{ GeV}$; the background regions are $1.52 \leq M(p\pi^+\pi^-) \leq 1.63 \text{ GeV}$ and $1.81 \leq M(p\pi^+\pi^-) \leq 1.90 \text{ GeV}$.

¹⁶See S. M. Berman and M. Jacob, Phys. Rev. **139**, B1023 (1965).

¹⁷N. Barash-Schmidt *et al.*, Rev. Mod. Phys. **41**, 109 (1969).