Production of the Δ(1950) by one-pion exchange in $\pi^+ p$ interactions at 13 GeV/c*

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(Received 16 April 1975)

We have observed the production of high-mass $I = \frac{3}{2}$ baryon resonances in $\pi^+ p$ interactions at 13 GeV/c. The most prominent of these is found to be the F_{37} Δ(1950). It is produced by one-pion exchange and the data are well described by on-shell $\pi^+ p$ phase shifts. Decays into $p\pi^+$ and $p\pi^+\pi^0$ are observed and the Δ(1950) is found to have a mass 1.880 ± 0.010 GeV and width of 0.180 ± 0.030 GeV with a production cross section of 43 ± 4 μb.

I. INTRODUCTION

Single-particle exchange has usually been invoked to study resonant boson states in a formation model. Baryon resonances, on the other hand, have been studied in detail through phase-shift analyses of formation experiments. In this paper we present data on the production of $I = \frac{3}{2}$ baryon resonances produced by one-pion exchange (OPE) from $\pi^+ p$ interactions at 13 GeV/c. In particular we observe the Δ(1950) F_{37} and the Δ(1670) D_{33} produced in the reaction

$$\pi^+ p \to \Delta^{++} \pi^+ \pi^- \tag{1}$$

with the $\pi^+\pi^-$ system dominated by ρ and f production. The names we associate with these resonances are those in current use in the Particle Data Group tables.[1] The only previously reported data on the Δ(1950) in the production mode were in $K^+ p$ interactions at 10 GeV/c.[2] We observe both elastic and inelastic decays of the Δ(1950) and compare the mass and width with values extracted from partial-wave analysis of elastic-scattering data.[3] In addition we present values for the mass, width, branching ratio, and production cross section for the Δ(1950). The data presented below are based upon a $\pi^+ p$ exposure of 34.3 events/μb of the SLAC 82-inch hydrogen bubble chamber, at 13 GeV/c.

II. DATA

The reactions in which we observe the Δ(1950) production are

$$\pi^+ p \to p\pi^+\pi^+\pi^- \tag{2}$$

$$\pi^+ p \to p\pi^+\pi^+\pi^-\pi^0. \tag{3}$$

In each reaction there is an inherent ambiguity due to the presence of two π^+'s; however, if these pions are ordered by center-of-mass longitudinal momentum only the slower pion is observed to resonate in the observed Δ states. In the following, this natural association is used without subscript and each plot contains only one combination per event.

The $\pi^+ p$ mass spectrum shows evidence of strong resonance production [see Fig. 1(a)], with the Δ(1950) appearing as a minor companion to the Δ(1236). The Δ(1950) mass region is given on an expanded scale [see Fig. 1(b)] to exhibit the shape and significance of the signal. Both of these plots are restricted to events with $-t'(p \to \Delta) < 0.3$ (GeV/c)^2. This cut is minor and does not exclude any resonance production except in other channels such as coherent 3π production. The $\pi^+\pi^-$ mass distribution for events in the Δ(1950) mass region

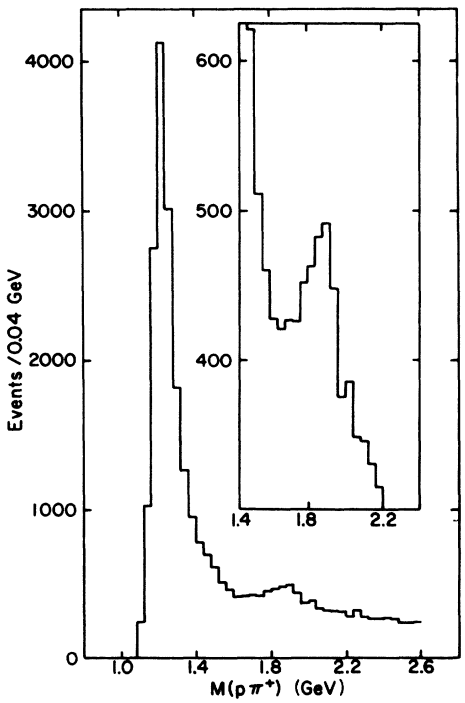

FIG. 1. Mass distribution of the proton and slow π^+ from the reaction $\pi^+ p \to p\pi^+\pi^+\pi^-$ with $-t'(p \to \Delta) < 0.3$ (GeV/c)^2. The inset shows the Δ(1950) region on an expanded scale.

$[1.67 < M(p\pi^+) < 2.09$ GeV] (see Fig. 2) is dominated by ρ and f production and is consistent in all respects with a one-pion-exchange production mechanism.

III. COMPARISON TO THE ELASTIC-PHASE-SHIFT DATA

Since the production of the $\Delta(1950)$ appears to be dominated by OPE, the data should exhibit the same features as those of formation experiments apart from effects due to the off-mass-shell behavior of the pion. We have used the CERN theoretical phase-shift results,[3] the principal contributions of which are shown in Fig. 3, to compare with our experimental data. In order to make this comparison, however, we have to take into account the effect of other channels giving a background in the $\Delta(1950)$ region. The main source of background is the reflection from the diffractively produced "A" region which creates a broad smooth distribution mass under the $\Delta(1950)$. We have compared the $p\pi^+$ mass spectrum for $-t'(p \to \Delta) < 0.5$ (GeV/c)^2 and $M(\pi^+\pi^-) < 1.5$ GeV with the predictions from the elastic-phase-shift data, [see Fig. 4(a)] and added a linear background which amounts to 50% of the data at the peak of the $\Delta(1950)$ to account for the "A" reflection. This background can be reduced substantially by choosing only those events for which the Δ has decayed backwards, determined by the angle of the final-state proton with respect to the initial proton in

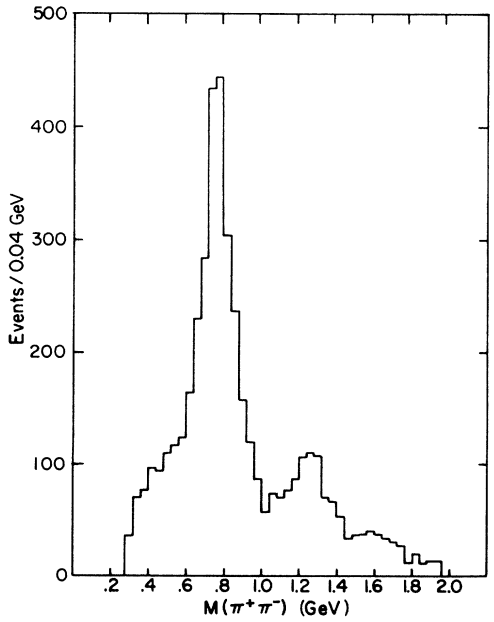

FIG. 2. Mass distribution of the $\pi^+\pi^-$ system from the reaction $\pi^+p \to p\pi^+\pi^+\pi^-$ with $-t' < 0.3$ (GeV/c)^2 and $1.67 < M(p\pi^+) < 2.09$ GeV.

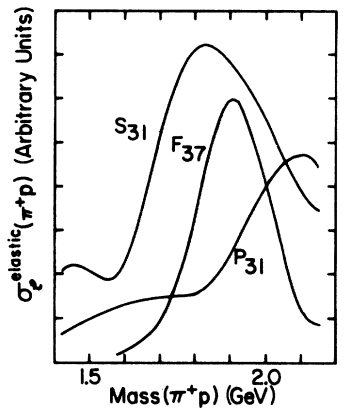

FIG. 3. The principal partial cross section of the on-shell phase shifts obtained from Ref. 3.

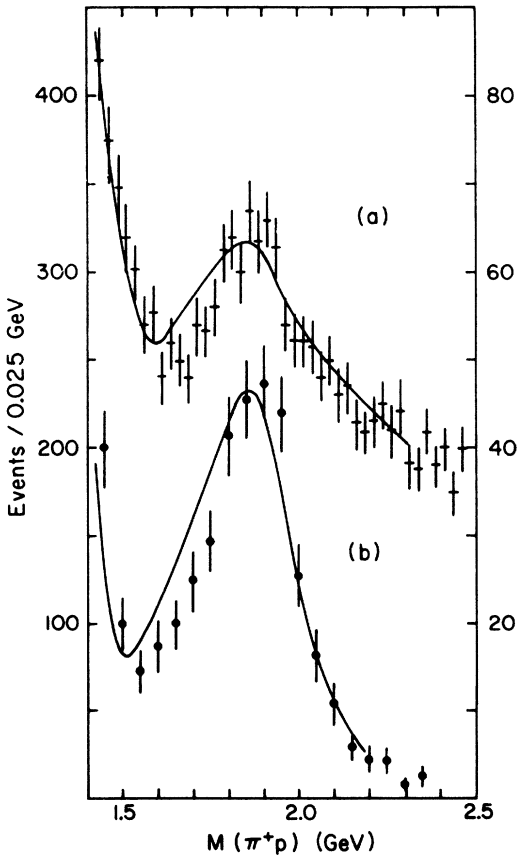

FIG. 4. Mass distribution of the $p\pi^+$ system from the reaction $\pi^+p \to p\pi^+\pi^+\pi^-$ with $-t' < 0.5$ (GeV/c)^2 and $M(\pi^+\pi^-) < 1.5$ GeV. The solid lines are the results of a calculation using the on-shell elastic scattering phase shifts with a quadratic background. (a) is for all events with the above cuts. (b) has the additional restriction that $\cos\theta_J < 0.0$.

the Δ center-of-mass system, that is, $\cos\theta_J < 0$. For this selection only 2% of the events in the Δ(1950) region suffer any reflective background for $M(3\pi) < 2.5$ GeV. The $p\pi^+$ mass spectrum for $\cos\theta_J < 0$ [see Fig. 4(b)] agrees with the predictions of the elastic-phase-shift data with a background which is nearly zero. The curves (see Fig. 4) represent the expectations from $\pi^+ p$ elastic scattering plus a polynomial (essentially linear) background where no modifications for the off-mass-shell nature of the pion have been included. Explicitly

$$\frac{d^2\sigma}{dM\, d\cos\theta} \propto M^2 Q \frac{d\sigma_{\pi^+ p}(M,\theta)}{d\cos\theta} \left\langle m^2 q \sigma_{\pi^+\pi^-}(m) \frac{1}{(t-\mu^2)^2} \right\rangle,$$

where Q, M, and θ are respectively the $\pi^+ p$ center-of-mass momentum, mass, and scattering angle, with an average being taken over the $\pi^+\pi^-$ vertex and pion propagator. The $\cos\theta_J$ distribution also agrees well with the elastic $\pi^+ p$ scattering (see Fig. 5) where $\cos\theta_J$ is shown for $1.75\ \text{GeV} < M(p\pi^+) < 2.05$ GeV. The curve which represents the elastic-scattering data is normalized to events for $\cos\theta_J < 0$. This clearly illustrates the effect of the contribution of the 3π diffractive background to the region $\cos\theta_J > 0$. For $\cos\theta_J < 0$ the Treiman-Yang angle in the Δ(1950) region is distributed isotropically.

The elastic-scattering cross section for on-shell $\pi^+ p$ scattering gives an excellent description of the data and by including off-shell modifications to the partial waves; even better agreement can be obtained by varying the various range parameters associated with each partial wave.

IV. PRODUCTION AND DECAY PROPERTIES OF THE RESONANCE

Because of the good agreement with the phase-shift data and the form of the angular distribution it seems clear that the enhancement is dominantly the F_{37} Δ(1950). This fact is further borne out by an examination of the moments of the angular distribution. Although these are complicated by the reflection of the 3π diffractive system there is clear evidence for structure up to and including $L = 6$. This is particularly true for events with $\cos\theta_J < 0$ where the structure in the $L = 6$ moment has a mass and a width consistent with those seen in the over-all mass spectrum. In the following analysis we have considered the enhancement to be a single F_{37} state, although the errors do reflect possible admixtures of D_{35} Δ(1890) and the effect of the s-wave background.

In addition to the decay of the Δ(1950) to $p\pi^+$, we have observed a significant $p\pi^+\pi^0$ decay which appears in reaction (3). In order to obtain the parameters of the resonance we have fitted the appropriate mass spectra to quadratic backgrounds plus a Breit-Wigner shape for the resonance of the form

$$\frac{\Gamma}{(M^2 - M^{*2})^2 + (\Gamma M)^2},$$

where

$$\Gamma = \Gamma^0 \frac{M^* q\, U_l(Rq)}{M q_0 U_l(Rq_0)}$$

is used to take into account angular momentum barrier effects.[4] The form of $U_l(X)$ is $(1/2X^2) \times Q_l(1 + 1/2X^2)$, and because the results are insensitive to variations of the range parameter R between 2 and 6 we have fixed the value at $(R = 4)$ $(\text{GeV}/c)^{-1}$, also in accord with previous results.[2]

A good fit is obtained to the relevant mass spectra (see Figs. 6 and 7) for $-t'(p \to \Delta) < 0.3$ $(\text{GeV}/c)^2$. In the case of the $p\pi^+$ mass spectrum (see Fig. 6) a single $l = 3$ Breit-Wigner distribution has been used and the tail of the Δ(1236) has been included, with no other cuts except the restriction of the four-momentum transfer. The contribution of the reflective background discussed earlier is adequately incorporated

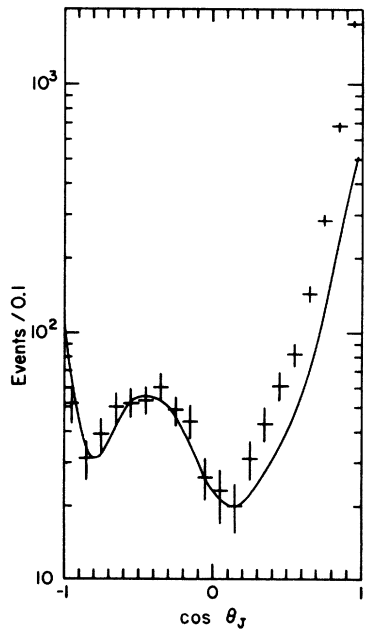

FIG. 5. The distribution of $\cos\theta_J$ for $1.75 < M(p\pi^+) < 2.05$ GeV and $-t' < 0.5$ $(\text{GeV}/c)^2$ and $M(\pi^+\pi^-) < 1.5$ GeV. The curve which represents the elastic-scattering data is normalized to events with $\cos\theta_J < 0.0$.

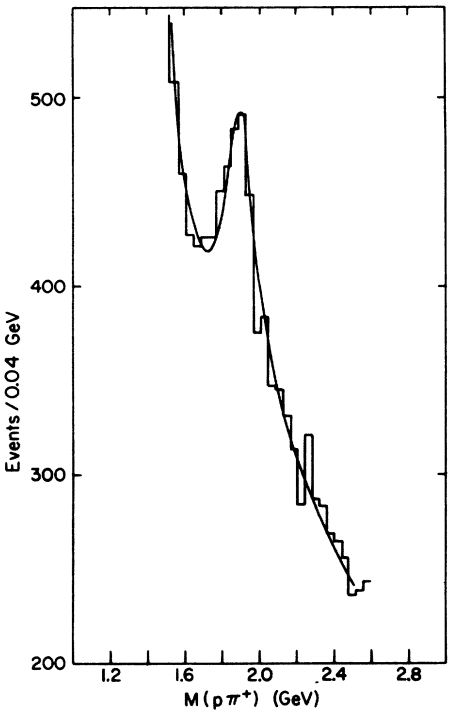

FIG. 6. Mass distribution of the $p\pi^+$ system from $\pi^+p \to p\pi^+\pi^+\pi^-$ with $-t' < 0.3$ $(\mathrm{GeV}/c)^2$. The solid line is a best fit using an $l = 3$ Breit-Wigner distribution for the $\Delta(1950)$.

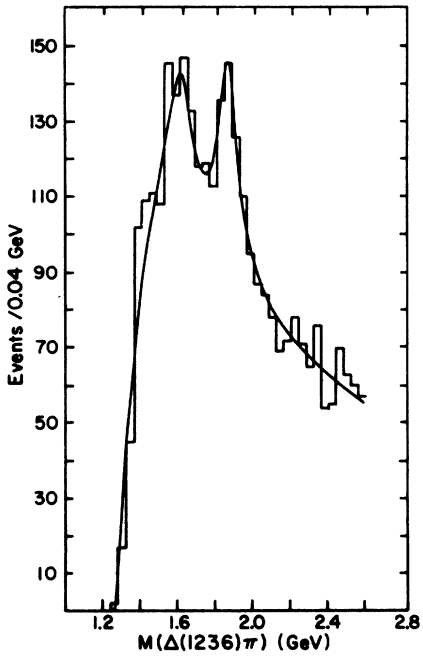

FIG. 7. Mass distribution of the $p\pi^+\pi^0$ system from $\pi^+p \to p\pi^+\pi^+\pi^-\pi^0$ with $-t'(p \to \Delta) < 0.3$ $(\mathrm{GeV}/c)^2$ and the $\Delta(1236)^{++}$ selected. The solid line is a best fit using an $l = 3$ Breit-Wigner distribution for the $\Delta(1950)$ and an s-wave Breit-Wigner distribution for the $\Delta(1670)$.

in the background function, although the effect of the other partial waves shown in Fig. 3 tends to increase the width of the observed peak. The $p\pi^+\pi^0$ mass spectrum from reaction (3) for $-t' < 0.3$ $(\mathrm{GeV}/c)^2$ and $M(p\pi^+) < 1.4$ GeV corresponding to the intermediate $\Delta(1236)$ π^0 decay exhibits two enhancements (see Fig. 7), one of which corresponds to the $\Delta(1950)$. The only additional cut on these data is the removal of ω^0 events, which is a very clean procedure. No other resonance production causes any serious reflection problems. The spectrum has been fitted with a quadratic background together with an $l = 3$ Breit-Wigner distribution for the $\Delta(1950)$ and an s-wave Breit-Wigner distribution for the lower enhancement, which we identify with the $\Delta(1670)$.

In addition to analyzing the $\Delta^{++}\pi^0$ decay of these resonances we have looked for the decays $\Delta^+\pi^+$, $p\rho^+$, and uncorrelated $p\pi^+\pi^0$. We do observe the $\Delta(1950)$ in the $\Delta^+\pi^+$ channel with a magnitude which gives a ratio of $\Delta^+\pi^+/\Delta^{++}\pi^0$ of $(60 \pm 15)\%$, in good agreement with the expected 44%. The $p\rho^+$ system is more difficult to analyze because of the large width of the ρ. There is a signal in the correct place but it appears to be mainly a result of the reflection of the $\Delta\pi$ decay. Our conclusion is that the decay of the $\Delta(1950)$ into $p\pi^+\pi^0$ proceeds entirely through $\Delta\pi$, although we cannot rule out some admixture of uncorrelated $p\pi^+\pi^0$ or $p\rho^+$. The same result appears to be true for the $\Delta(1670)$, although here the restricted phase space makes analysis virtually impossible.

The results of the above fits are presented in Table I for the mass and width of each of the fit-

TABLE I. The mass and width of the $\Delta(1950)$ and $\Delta(1670)$ obtained from fitting the mass spectra and the production cross sections corrected by the appropriate isospin factors.

Decay mode	M (GeV)	Γ_0 (GeV)	Resonance	Cross section ($\propto\Gamma_0$) (μb)
$p\pi^+$	1.885 ± 0.008	0.210 ± 0.030	$\Delta(1950)$	28 ± 3
$p\pi^+\pi^0$	1.870 ± 0.010	$0.155^{+0.040}_{-0.020}$	$\Delta(1950)$	15 ± 3
$p\pi^+\pi^0$	1.600 ± 0.010	$0.180^{+0.035}_{-0.020}$	$\Delta(1670)$	23 ± 3

ted enhancements. Within errors the parameters of the Δ(1950) agree between the two channels and the width appears to be somewhat narrower than that obtained from the phase-shift analysis.

In Table I are also presented the results for the production cross section of each of these resonances when the $p\pi^+\pi^0$ decay is assumed to proceed through $\Delta(1236)\pi$ and the appropriate cross section for unseen decays is made. These numbers give a ratio of $p\pi^+\pi^0/(p\pi^+ + p\pi^+\pi^0)$ of $(35 \pm 8)\%$. If the $p\pi^+\pi^0$ decay were assumed to be pure $p\rho$ this branching ratio would change to 30%, which is not a significant difference. There is no evidence for the $p\pi^+$ decay of Δ(1670), although a significant branching ratio of ~20% cannot be ruled out. Our best estimates for the mass and width of the Δ(1950) using the combined data are $M = 1.880 \pm 0.010$ GeV and $\Gamma_0 = 0.180 \pm 0.030$ GeV, consistent with the values of $\Gamma = 1.895 \pm 0.015$ GeV and $\Gamma_0 = 0.230 \pm 0.05$ GeV obtained in the $K^*(890)$ Δ(1950) analysis.[2]

Table II presents some partial cross sections for particular quasi-two-body final states involving the Δ(1950) and similar ones for the Δ(1236) which have been published previously.[5,6] The cross sections are calculated including the tails of the resonance and with the background under each resonance subtracted. The events used were for $-t' < 0.3$ GeV$/c^2$, and no correction was applied since no enhancement is observed at higher values of four-momentum transfer squared.

TABLE II. Cross sections for ρ and f production in association with either Δ(1236) or Δ(1950).

Channel	Cross section ($\pm\Gamma_0$) (μb)
Δ(1950)ρ	25 ± 4
Δ(1950)f	6 ± 2
Δ(1236)ρ	248 ± 12
Δ(1236)f	115 ± 7

V. SUMMARY

We have observed two $I = \frac{3}{2}$ baryon resonances in the 1.6–2 GeV mass region in π^+p interactions at 13 GeV$/c$. These resonances are produced by one-pion exchange, and the data are similar to on-shell $\pi\rho$ scattering. We have identified these resonances with the Δ(1950) F_{37} and the Δ(1670) D_{33} and measured their production and decay parameters to a higher precision than has been possible previously.

ACKNOWLEDGMENTS

We thank the SLAC 82-inch bubble chamber crew and the Purdue measuring staff for their assistance in making this experiment possible. We also acknowledge the contributions of Dr. T. A. Mulera and Dr. G. Thompson and Professor R. B. Willmann in the data reduction.

*Work supported in part by the U. S. Energy Research and Development Administration.

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