OBSERVATION OF THE $p\pi\pi$ DECAY MODE OF THE $N_{1/2}^*(1400)$ RESONANCE IN pp INTERACTIONS AT 22 GeV/c*

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Approximately 12 000 four-pronged interactions of 22-GeV/c protons in a hydrogen bubble chamber have been measured. In a sample of 1234 $pp\pi^+\pi^-$ events the final state is dominated by $\Delta^{++}(1236)$ production. Approximately 120 of these events are attributed to the $p\pi^+\pi^-$ decay of a resonant state with mass 1443 ± 15 MeV and width 100 ± 25 MeV identified with the $N_{1/2}^*(1400)$ resonance. There is also strong evidence for a $p\pi\pi$ enhancement with a central mass value of 1693 MeV.

The first evidence for a baryon resonance with a mass near 1400 MeV was in a pion-nucleon phase-shift analysis[1] which assigned the state to a P_{11} resonance, $N_{1/2}^*(1400)$.[1-3] More recently, counter experiments have provided evidence for production of 1400-MeV effects in both pion-nucleon and nucleon-nucleon interactions at momenta from ~5 to 30 GeV/c.[4] Bubble-chamber studies of Kp, πp, and pp interactions at momenta from ~1.5 to 28.5 GeV/c have shown enhancements in the 1400-MeV mass region in πN and $\pi\pi N$ invariant-mass spectra.[2,5,6] Attempts[6] have been made using the ideas of Deck and Ross and Yam[7] to interpret the $\pi\pi N$ enhancements as due to so-called kinematic effects. Although these calculations reproduce the general characteristics of the data well (broad enhancement at small $\pi\pi N$ mass), they are unable to account for the sharper structure observed in some investigations. Only the first Berkeley–University of California, Los Angeles collaboration (Gellert et al.[6]) at 6.6 GeV/c concludes that all of the 1400-MeV effect in their data is due to such a kinematic mechanism. A preliminary report of the Illinois group (Grether et al.[6]) at 8.0 GeV/c and the recent double-Regge-pole analysis by the Berkeley–University of California, Los Angeles group (Berger et al.,[6] again at 6.6 GeV/c) do not reach definite conclusions, while the remaining three studies cited in Ref. 6 show that the 1400-MeV structure in their data cannot be fully accounted for by kinematic arguments. Observation of a 1400-MeV effect in such a wide variety of experimental situations strongly suggests its interpretation as a resonance. In addition, several of these studies indicate a more complicated structure in the $\pi\pi N$ invariant-mass spectra, in particular a second enhancement near 1700 MeV.

In this note we report evidence for a well-defined 1400-MeV peak in the $p\pi^+\pi^-$ invariant-mass spectrum in the reaction

$$pp \to pp\pi^+\pi^- \qquad (1)$$

at 22 GeV/c. We identify this effect with the $N_{1/2}^*(1400)$ resonance. We also have strong evidence for a 1700-MeV enhancement in the same spectrum.

Approximately 70 000 pictures of interactions of 21.8-GeV/c protons with hydrogen were taken in the Brookhaven National Laboratory 80-in. bubble chamber. This film was scanned for all topologies in a limited fiducial volume which was chosen so that high-momentum (≥15 GeV/c) forward-going tracks could be measured to an accuracy of ~5%. All three- and four-prong events within this volume were measured in 80% of the film. The three-prong sample is included to take into account very slow protons which have insufficient energy to create a visible track. Measured events were reconstructed using a local version of HGEOM and kinematically fitted to the following reactions (where C denotes constraint):

$$pp \to pp\pi^+\pi^- \quad \text{(4C or 1C if from a three-prong)}, \qquad (1)$$

$$pp \to pp\pi^+\pi^-\pi^0 \quad (1C), \qquad (2)$$

$$pp \to pn\pi^+\pi^+\pi^- \quad (1C), \qquad (3)$$

using the program GUTS.[8] The sample for Reaction (1) includes 1234 events, which, with corrections for scanning and measurement losses, corresponds to a cross section of 1.36 ± 0.16 mb.

Mass spectra.—Reaction (1) is dominated by $\Delta^{++}(1236)$ production. The numbers of events having both, one, or no $p\pi^+$ mass combination in the Δ^{++} band (1225 ± 125 MeV) are 12, 806, and 416, respectively. The $p\pi^-$ mass spectrum shows only small signals for the production of resonances, and there is no evidence for doubleresonance production.

The gross $p\pi^+\pi^-$ invariant-mass distribution is shown in Fig. 1(a). Strong enhancements are seen at masses of ~1450 and ~1700 MeV. The statistical significance of these features has been investigated by fitting[9] this spectrum with three theoretical expressions: (a) a background term, (b) a background term plus one Breit-Wigner resonance expression, and (c) a background term plus two resonance expressions. The same background term, which consists of a two-parameter polynomial plus the contribution[10] of the Feynman graph of Fig. 1(b) [hereafter called the kinematic or one-pion-exchange (OPE) distribution] is used in all three fits. We justify this construction of the background by the observation that for our data the gross $p\pi^+\pi^-$ mass spectrum is the sum of two distributions, one for $\Delta^{++}\pi^-$ combinations and the other for non-$\Delta^{++}\pi^-$ combinations. The former is expected (in the absence of resonance effects in the $\Delta^{++}\pi^-$ channel) to be approximately represented by the mechanism of Fig. 1(b), while the polynomial background is chosen to characterize the latter distribution. The results of the three fits are given in Table I. We conclude that the 1450- and 1700-MeV effects are statistically significant in the sense that the two-resonance fit provides the only resonable representation of the data.

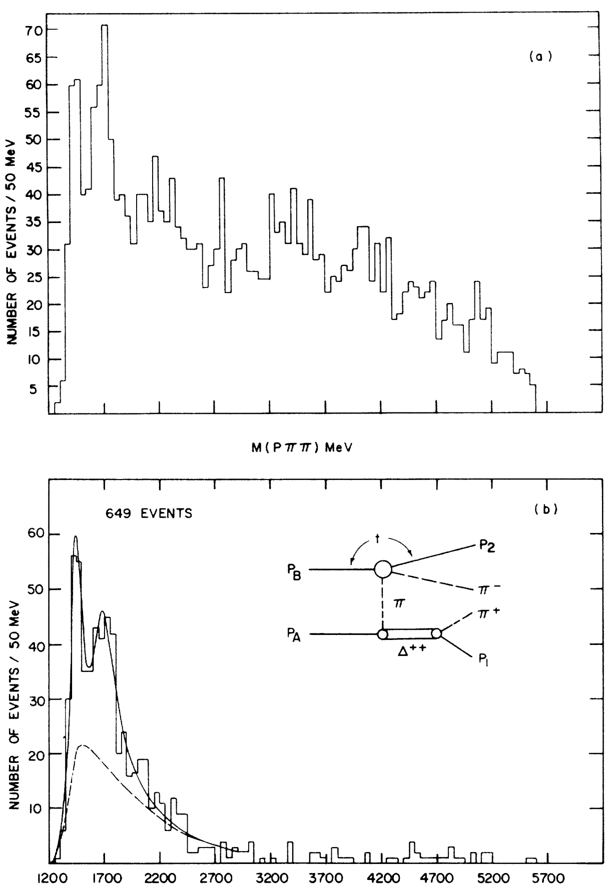

FIG. 1. (a) $p\pi^+\pi^-$ invariant-mass distribution; 2468 combinations, two per event. (b) $p_1\pi^+\pi^-$ invariant-mass distribution for $p_1\pi^+$ mass in the Δ^{++} region (1225 ± 125 MeV), $p_2\pi^+$ mass outside the Δ^{++} region, and $p_2\pi^-$ mass greater than 1640 MeV. The solid curve is a fit to the histogram of two resonance expressions plus the kinematic background term. The dashed curve is the contribution to the fit of the background term.

A more definitive test of the contribution of the kinematic OPE mechanism is made by considering the selected $\Delta^{++}\pi^-$ mass distribution shown in Fig. 1(b). The data are restricted by requiring that the $p_1\pi^+$ mass be in the Δ band (1225 ± 125 MeV), that the $p_2\pi^+$ mass be outside the Δ band, and that the $p_2\pi^-$ mass be in the diffraction region (>1640 MeV). [p_1 and p_2 are the final-state protons defined by these criteria and by Fig. 1(b).] This $\Delta^{++}\pi^-$ distribution is fitted[9] first with a background term only, and then with a background term plus, successively, one and two resonance expressions. For these selected data the background is assumed dominated by the OPE mechanism[10] and no polynomial is used in the background expression. Results of these fits are presented in Table I. The OPE distribution alone provides a poor representation of the data, and again the two-resonance hypothesis is the most acceptable. In this case the single-resonance fit is also acceptable; however, the adjusted mass and, in particular, the width of the resonance term differ significantly from values obtained in the analogous fit to the gross $p\pi^+\pi^-$ distribution. We note that the two-resonance fits to the gross and selected data are reasonably consistent with respect to the contributions and the masses and widths of the resonance terms and also with respect to the OPE background contribution. We conclude that two resonancelike structures imposed on a background is the most adequate interpretation of both the gross and selected data. We associate the 1440-MeV enhancement with the $N_{1/2}^*(1400)$. With corrections for scanning and measurement bias[11] the cross section for $pp \to pN_{1/2}^*(1400), N_{1/2}^*(1400) \to p\pi^+\pi^-$ is $155 \pm 30 \mu b$. The identification of the 1700-MeV effect with previously established resonances is unclear.[12]

Spin and parity.—Spin and parity tests have

Table I. Results of fits to gross and selected $p\pi^+\pi^-$ distributions. The contribution of resonance terms, where included, is indicated by N, while M and Γ refer to the central mass and to the width, respectively. The contribution of the OPE background is referred to as $N_{\rm OPE}$. Details of the fitting procedure are given in Ref. 9.

Data	Number of resonance terms	N_1	M_1 (MeV)	Γ_1 (MeV)	N_2	M_2 (MeV)	Γ_2 (MeV)	$N_{\rm OPE}$	χ^2	Probability (%)
Gross	0							811	65[a]	<0.1
	1	503	1525	368				197	65[a]	<0.05
	2	112	1446	104	193	1693	197[b]	402	38[c]	~8
Selected	0							599	77	<0.01
	1	186	1473	244				413	45	~6
	2	105	1440	100	171	1693	270	323	30	~40
Final parameter estimates[d]		120±15	1443±15	100±15	190±40	1693±15	235±50	375±75		

[a]The large χ^2 here arises from the structure in the low-mass region, 1350-2000 MeV.
[b]The width here is required to be less than 200 MeV. If unconstrained, it tends to an unreasonably large value (with little improvement in χ^2) which is an attempt to compensate for some inadequacy of the polynomial background form in representing the data above 2000 MeV.
[c]Here the principal contribution to the χ^2 is from the high-mass region, 2000-3000 MeV.
[d]Absolute resonance contributions are given for the gross sample, with special corrections for loss of $N_{1/2}^*(1400)$ (see Ref. 11). The $N_{\rm OPE}$ is corrected for the contribution above 3000 MeV.

been applied to events in the $N_{1/2}^*(1400)$ region assuming first a $\Delta^{++}\pi^-$ decay and second a general $p\pi^+\pi^-$ decay.[13] The decay distributions are consistent with $J^P = \frac{1}{2}^+$ for either hypothesis, but other possibilities are not excluded.

Δ association.—We have studied the $\Delta\pi$ decay of the $N_{1/2}^*(1400)$ by plotting the $p_1\pi^+$ and $p_1\pi^-$ mass distributions for different regions of the $p_1\pi^+\pi^-$ mass spectrum. The correlation of these distributions is consistent with a large value for the ratio $(N_{1/2}^* \to \Delta\pi)/(N_{1/2}^* \to \text{all } p\pi^+\pi^-)$ and not inconsistent with the value 1. A more quantitative estimate of this ratio from these data is not possible because of the kinematic restrictions on the $p_1\pi^+$ and $p_1\pi^-$ mass range for events with $p_1\pi^+\pi^-$ mass in the $N_{1/2}^*(1400)$ and also because of the Δ^{++} dominance of the background.

Production mechanism.—In Fig. 2 is shown the $N_{1/2}^*(1400)$ four-momentum-transfer distribution. The four-momentum transfer is from proton p_A to the $p_1\pi^+\pi^-$ system as shown in the Feynman graph of Fig. 1(b). The solid curve shown is the result of fitting the data [for $|t| \leq 0.25$ (GeV/c)^2] with the expression $\exp(bt)$ and corresponds to the value $b = 18.0 \pm 2.3$ (GeV/c)$^{-2}$. This value of the slope parameter may be compared with values from ~14 to 24 (GeV/c)$^{-2}$ found in pp interactions in the counter experiments,[4] and with values ~6 (GeV/c)$^{-2}$ (Bell et al.[5]) and ~11 (GeV/c)$^{-2}$ (Lamsa et al.[6]) found in πp interactions using bubble-chamber techniques.

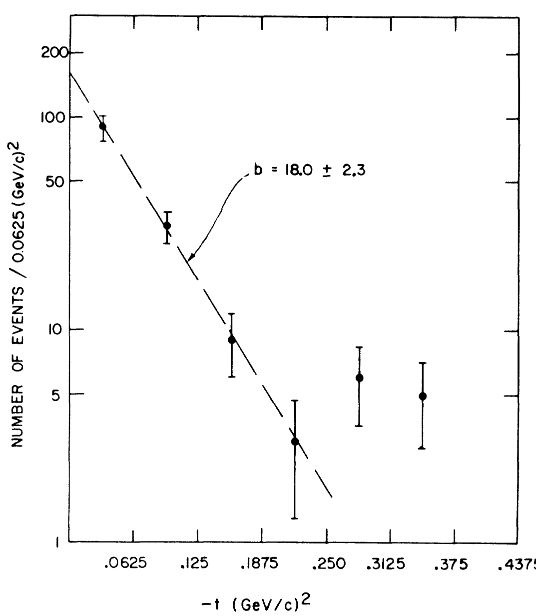

FIG. 2. Distribution in the square of the four-momentum transfer to the $N_{1/2}^*(1400)$. Events have been selected with $p_1\pi^+\pi^-$ mass between 1400 and 1500 MeV, with $p_1\pi^+$ in the Δ^{++} region (1225±125 MeV), $p_2\pi^+$ outside the Δ^{++} region, and $p_2\pi^-$ mass greater than 1640 MeV. The four-momentum transfer is from p_A to $p_1\pi^+\pi^-$, where p_A is the initial proton having the smaller four-momentum transfer to p_1. The first bin has been corrected for lost events in the forward direction. The fit for the backward-going $N_{1/2}^*(1400)$ only yields a value of b comparable with that given in this figure.

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[8]Events assigned to Reaction (1) fulfill the following requirements: (a) $\chi^2 < 30$ (4C), $\chi^2 < 13$ (1C); (b) ionization of all measured tracks is consistent with particle assignment. Approximately 4% of these events have two different fits which cannot be resolved on the basis of ionization. These events were excluded from the sample used for the study. Contamination from Reaction (2) is a few percent. Background from Reaction (3) is consistent with zero.

[9]Fits to the gross and selected $p\pi^+\pi^-$ distributions are based on the maximum likelihood method. Values of χ^2 are calculated by numerical integration (resolution 10 MeV) of the fitted curves over 50-MeV intervals. We fit only for masses less than 3 GeV. Errors in adjusted parameters are not determined formally from the fits, but are based on a qualitative evaluation of the variation in the "goodness" of the fit with changes in parameters. S-wave relativistic Breit-Wigner expressions cut off beyond two widths from the central mass value are used for the resonance terms. The central mass, width, and contribution of each resonance term and the contributions of the OPE and polynomial terms are all adjusted in the fitting procedure.

[10]The details of the kinematic calculation are the following: (a) The cross-section formula is given by Eq. (3.30) of E. Ferrari and F. Selleri, Nuovo Cimento Suppl. 24, 453 (1962). This is a standard OPE calculation. (b) The π^-p diffraction scattering at the upper vertex of the Feynman diagram is assumed to obey $d\sigma/dt \sim \exp(9t)$, where t is defined in the figure. (c) The mass dependence of the Δ^{++} resonance at the lower vertex of the Feynman diagram is represented by a standard nonrelativistic Breit-Wigner expression. The calculated distribution is insensitive to the form of the Δ^{++} mass curve: A Breit-Wigner form or a δ function yield essentially the same result. (d) The virtuality of the exchanged pion and other off-shell effects are included by using the form factors of H. P. Dürr and H. Pilkuhn, Nuovo Cimento 40A, 899 (1965), as fitted by G. Wolf, Phys. Rev. Letters 19, 925 (1967). The calculated distribution is insensitive to the use of the form factors. (e) Two other diagrams of magnitude comparable with the diagram used, but whose contributions approximately cancel, are neglected. See Ross and Yam (Ref. 7) for details on this point. For general discussion of these calculations also see Ref. 7.

[11]We have examined the $\Delta^{++}\pi^-$ mass spectrum separately for forward- and backward-going p_1 in the center-of-mass system. The $N_{1/2}^*(1400)$ signal is more pronounced in the backward data. Since the $N_{1/2}^*(1400)$ is produced very peripherally, forward $p_1\pi^+\pi^-$ events are systematically lost due to difficulties in scanning and measuring events with a very slow recoil proton.

[12]Lovelace (Ref. 3) lists seven pion-nucleon resonances between ~1650 and ~1750 MeV. Most are well established, have large widths, and are highly inelastic. Though we have fitted the 1700-MeV feature in our data with a single resonance term we do not exclude the possibility that it has a more complicated structure. The $p\pi^+\pi^-$ mass distribution in 20-MeV bins (not shown here) provides some suggestion of this; specifically, the 1700-MeV effect consists of a sharp feature centered around 1730 MeV with a shoulder on the low-mass side.

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