phase-shift analysis.

[3] S. P. Almeida et al., Nuovo Cimento 50A, 1000 (1967); R. B. Bell et al., Phys. Rev. Letters 20, 164 (1968); W. E. Ellis, D. J. Miller, T. W. Morris, R. S. Panvini, and A. M. Thorndike, Phys. Rev. Letters 21, 697 (1968). For earlier contributions on the $N^*(1470)$ see, for example, A. H. Rosenfeld et al., Rev. Mod. Phys. 40, 77 (1968). We shall follow these authors and adopt $N^*(1470)$ as the notation for the P_{11} state.

[4] E. Gellert et al., Phys. Rev. Letters 17, 884 (1966).

[5] E. L. Berger, Phys. Rev. Letters 21, 701 (1968), and references therein.

[6] D. V. Bugg et al., Phys. Rev. 146, 980 (1966).

[7] L. Hulthén and M. Sugawara, in Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 39, p. 1.

[8] For the determination of the momentum transfers, center-of-mass quantities, etc., the neutron-momentum four-vector was taken as $p_d - p_s$, where p_d and p_s are the deuteron and spectator momentum four-vectors, respectively.

[9] 43 uniquely defined events with a secondary scatter on one of the tracks (and therefore measured as a straight line) and nine events with a spectator momentum of more than 280 MeV/c were not included in the analysis. It was checked, however, that neglecting these events, which are of poorer quality, does not introduce any bias.

[10] W. Lee, thesis, University of California, Radiation Laboratory, Report No. UCRL-9691, May, 1961 (unpublished); R. J. Glauber and V. Franco, Phys. Rev. 156, 1685 (1967); A. Dar and A. Gal, Phys. Rev. Letters 21, 444 (1968).

[11] Different estimated backgrounds were used in the various fits. Also, fits with Breit-Wigner distributions of the Jackson type [see J. D. Jackson, Nuovo Cimento 34, 1644 (1964)] were attempted. The best values for the mass of the $N^*(1470)$ did not vary by more than 10-15 MeV by changing the shape of the background or the type of the Breit-Wigner curve. The width and production rates are, however, more sensitive to the shape of the background. $M = 1.20$ GeV was used for the mass of the "$N^*(1236)$" in the derivation of the best fit.

[12] Jackson, Ref. 11.

[13] This is also suggested by the constant cross sections for the reaction $pp \to pN^{*+}(1400)$ at different energies in contrast to the rapid decrease with energy in the reaction $pp \to pN^{*+}(1236)$ (see Ref. 1).

[14] M. N. Kreisler, F. Martin, M. L. Perl, M. J. Longo, and S. T. Powell, III, Phys. Rev. Letters 16, 1217 (1966).

[15] The cross section for Reaction (6) in deuterium has to be corrected for the Glauber "shadow effect," which is about 10%.

[16] N. F. Bali, G. F. Chew, and A. Pignotti, Phys. Rev. Letters 19, 614 (1967); H. M. Chan et al., Nuovo Cimento 49A, 157 (1967). For further references, see Ref. 5.

[17] The values for the adjustable parameters are the same as in Berger's fit ($\alpha_p \equiv 1, \alpha_\pi' = 1.2, S_{10} = 1$ GeV, $S_{20} = 2M_pM_n$). No cuts were imposed on t_n or on the $p_p\pi^-$ invariant mass, and $G_\pi(t_n) = (0.5\pi\alpha_\pi' m_\pi)^2$ was assumed for $|\alpha_\pi| \geq 1$ to avoid the pole in $G_\pi(t_\pi)$.

[18] R. Dolen, D. Horn, and C. Schmid, Phys. Rev. 166, 1768 (1968).

$p\pi^+\pi^-$ ENHANCEMENTS IN THE REACTION $pp \to pp\pi^+\pi^-$ AT 24.8 GeV/c

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A study of the reaction $pp \to pp\pi^+\pi^-$ at 24.8 GeV/c, based on 3250 events, gives strong support for the production of resonant $p\pi^+\pi^-$ states at 1.423 ± 0.027 and 1.688 ± 0.023 GeV.

A number of experimenters studying reactions of the type $xp \to xp\pi^+\pi^-$, where $x = \pi$,[1] K,[2,3] or p,[4-11] have reported enhancements in the final-state $p\pi^+\pi^-$ invariant-mass spectrum. The actual number of low-mass enhancements, their interpretation as either resonances[4,7,10,11] or kinematic effects,[8] and their connection with the peaks seen in earlier missing-mass experiments[12-14] are all unresolved questions.

We report further results on the reaction $pp \to pp\pi^+\pi^-$ at 24.8 GeV/c.[15] These data were obtained from approximately 15 500 measured three- and four-prong events obtained in a 3.4-event/μb exposure of the Brookhaven National Laboratory 80-in. hydrogen bubble chamber. In 90% of the film, only those four prongs having a slow proton identifiable by ionization were measured. This selection of events having one proton with a momentum below about 1 GeV/c allowed us to measure about half the total number of three and four prongs. A cross section of 1.5 ± 0.2 mb is obtained for this final state after correcting for the loss of events without slow protons. We note that discriminating against events without slow protons cannot seriously distort the highly peripheral low-mass $p\pi^+\pi^-$ spectrum, since in that 10 % of the film in which all three and four prongs were measured, only 7.3 % of $pp\pi^+\pi^-$ events having $p\pi^+\pi^-$ masses below 2 GeV did not have a slow proton identified by ionization. Furthermore, the structure of the $p\pi^+\pi^-$ spectrum below 2 GeV for this 7.3 % is consistent with that of the slow-proton events.

Copious Δ^{++} production via the quasi-three-body final state $\Delta^{++}p\pi^-$ is observed. However, the percentage cannot be accurately determined on account of the strong enhancement of the low-mass $p\pi^+\pi^-$ spectrum and the correlation between low-mass $p\pi^+\pi^-$ and $p\pi^+$ enhancements. The data are consistent with between 55 and 90% Δ^{++} formation.

In agreement with some other recent experiments[4,10,11,16] made to study the reaction $pp \to pp\pi^+\pi^-$ at high energies, two $p\pi^+\pi^-$ enhancements are observed, one at about 1.45 GeV and the other at about 1.69 GeV, as seen in Fig. 1. A Deck-type[18,19] background, obtained by modifying three-body ($p\Delta^{++}\pi^-$) phase space according to a prescription suggested by Stodolsky,[17] is also shown. A fit to the $p\pi^+\pi^-$ spectrum using such a background together with a single S-wave Breit-Wigner resonance, the dotted curve in Fig. 1, does not fit the data in the mass interval 1.45-1.60 GeV. An excess of 17 ± 12 events in the interval 1.45-1.50 GeV and a deficiency of 41 ± 17 events in the interval 1.50-1.60 GeV amount to a 3-standard-deviation effect, indicating the presence of resonance near 1.45 GeV. To determine the resonance masses and widths, the data were fitted by a function of the form

$$[\alpha_0/f^2 + \alpha_1 f_{\mathrm{BW}}(m_1, \Gamma_1) + \alpha_2 BW(m_2, \Gamma_2)]\varphi,$$

where f is a third-order polynomial in M, the $p\pi\pi$ invariant mass minus 1.217 GeV, f_{BW} is the standard S-wave Breit-Wigner function, φ is unmodified four-body phase space, and α_0, α_1, α_2 are the fraction of background and of two resonances, respectively. This fit is shown as the upper curve in Fig. 1. The parameters obtained from this fit are, in GeV,

$$m_1 = 1.406 \pm 0.010, \quad \Gamma_1 = 0.174 \pm 0.025;$$

$$m_2 = 1.675 \pm 0.010, \quad \Gamma_2 = 0.132 \pm 0.032.$$

The data were also fitted by a Deck-type[17,18] background plus two resonances yielding values of

$$m_1 = 1.427 \pm 0.023, \quad \Gamma_1 = 0.116 \pm 0.045;$$

$$m_2 = 1.698 \pm 0.011, \quad \Gamma_2 = 0.100 \pm 0.032.$$

Since a substantial fraction of the final state may not involve Δ^{++} production, it is not clear that a Deck-type background is relevant. We see no way of determining experimentally which of these two widely different choices for the shape of background is more appropriate. The entries in Table I are chosen so as to bracket approxi-

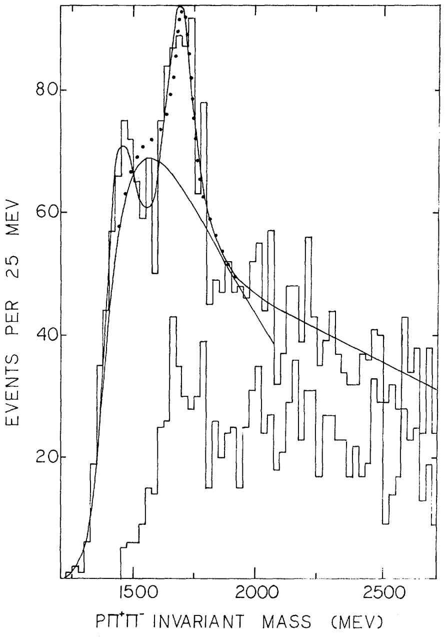

FIG. 1. $p\pi^+\pi^-$ invariant-mass distributions with two combinations per event (upper curve). (In only 28 events are both $p\pi^+\pi^-$ mass combinations below 2 GeV). In the lower histogram only those events having both $p_1\pi^+$ and $p_2\pi^+$ invariant masses greater than 1.3 GeV have been plotted. The curves are fits to the data described in the text.

Table I. Properties of $p\pi^+\pi^-$ enhancements. The values are combinations of results from the fits described in the text.

Mass (GeV)	Full width (GeV)	t dependence of resonance plus background[a] [(GeV/c)$^{-2}$]
1.423 ± 0.027	0.135 ± 0.064	9.6 ± 1.5
1.688 ± 0.023	0.116 ± 0.048	6.6 ± 0.9

[a] I.e., β in $e^{-\beta|t|}$.

mately the 1-standard-deviation limits of the parameters from the two fits described above. The resonant contributions α_1 and α_2 depend critically on the shape of background and could correspond to cross sections as large as 150 and 220 μb with the polynomial modification of phase space, or as small as 15 and 73 μb with the Deck-type background.

We note that the masses 1.423 and 1.688 GeV closely coincide with those of πN isobars seen in phase-shift analyses and those of $p\pi^+\pi^-$ enhancements reported by others[4,10,11,16].

The low mass of the 1.423-GeV enhancement precludes a determination of the branching fraction for the decay mode $\Delta^{++}\pi^-$ due to the small size of the $p\pi^+\pi^-$ Dalitz plot and the large Δ^{++} width.

In the case of the 1.688-GeV enhancement, a substantial contribution is observed for events having both $p\pi^+$ masses greater than 1.3 GeV, as seen in Fig. 1, thus indicating the presence of decay modes other than $\Delta^{++}\pi^-$.

The distribution of the four-momentum transfer between an initial-state proton and the final-state $p_1\pi^+\pi^-$ system[20] is well described by an exponential of the form $e^{-\beta|t|}$, in the range $0.02 < |t-t_{\rm min}| < 0.3$ (GeV/c)^2, where $t_{\rm min}$ is the minimum allowed momentum transfer for a given $p\pi^+\pi^-$ mass. The $p\pi^+\pi^-$ enhancements have values for β as listed in Table I.

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[1] R. B. Bell, D. J. Crennell, P. V. C. Hough, U. Karshon, K. W. Lai, J. M. Scarr, T. G. Schumann, I. O. Skillicorn, R. C. Strand, A. H. Bachman, P. Baumel, R. M. Lea, and A. Montwill, Phys. Rev. Letters 20, (1968).

[2] J. Wolfson, N. Gelfand, P. Leary, Bull. Am. Phys. Soc. 13, 704 (1968).

[3] R. Mercer, A. Callahan, R. Carson, B. Cox, D. Denegri, L. Ettlinger, D. Gillespie, G. Goodman, G. Luste, A. Pevsner, and R. Zdanis, Bull. Am. Phys. Soc. 13, 704 (1968).

[4] R. A. Jespersen, Y. W. Kang, W. J. Kernan, R. A. Leacock, J. I. Rhode, T. L. Schalk, and L. S. Schroeder, Phys. Rev. Letters 21, 1368 (1968).

[5] W. E. Ellis, P. L. Connolly, D. J. Miller, T. W. Morris, and R. S. Panvini, Bull. Am. Phys. Soc. 13, 682 (1968).

[6] Collaborating groups at Copenhagen, Helsinki, Oslo, and Stockholm Universities, in the Proceedings of the International Conference on Elementary Particles, Heidelberg, Germany, 1967, edited by H. Filthuth (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968).

[7] S. P. Almeida, J. G. Rushbrooke, J. M. Scharenguivel, M. Behrens, V. Blobel, N. C. Dehne, J. Diaz, R. Schafer, W. P. Swanson, I. Borecka, and G. Knies, Nuovo Cimento 50A, 1000 (1968).

[8] E. Gellert, G. A. Smith, S. Wojcicki, E. Colton, P. E. Schlein, and H. K. Ticho, Phys. Rev. Letters 17, 884 (1966).

[9] D. Grether, G. Ascoli, M. Firebaugh, E. L. Goldwasser, R. D. Sard, and J. Wray, Univerisity of Illinois Report No. COO-1195-78 (to be published).

[10] J. G. Rushbrooke, J. R. Williams, N. Barford, and K. Pongpoonsuksri, in the Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968 (to be published).

[11] H. Boggild, J. Eades, K. Hansen, H. Johnstad, R. Möllerud, L. Veje, Pl. Laurikainen, P. Lindblom, J. Tuominiemi, T. Jacobsen, S. O. Sörensen, O. Thingvold, G. Ekspong, L. Granström, S. O. Holmgrem, S. Nilsson, T. Olhede, U. Svedin, and N. Yamdagni, in the Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968 (to be published).

[12] C. Belletini, G. Cocconi, A. N. Diddens, E. Lillethum, J. P. Scanlon, A. M. Shapiro, and A. M. Wetherell, Phys. Letters 18, 67 (1965).

[13] E. W. Anderson, E. J. Blesser, G. B. Collins, T. Fujii, M. Menes, F. Turkot, R. A. Carrigan, Jr., R. M. Edelstein, N. C. Hein, T. J. McMahon, and I. Nadelhaft, Phys. Rev. Letters 16, 855 (1966).

[14] K. J. Foley, R. S. Jones, S. J. Lindenbaum, W. A. Love, S. Ozaki, E. D. Platner, C. A. Quarles, and E. H. Willen, Phys. Rev. Letters 19, 397 (1967).

[15] Preliminary results were already reported at the Spring Meeting of the American Physical Society, Washington, D. C., 22-25 April 1968. R. Ehrlich, R. J. Plano, R. Nieporent, J. B. Whittaker, C. Baltay, J. Feinman, P. Franzini, R. Newman, and N. Yeh, Bull. Am. Phys. Soc. 13, 682 (1968).

[16] A single broad enhancement is seen by the authors of Ref. 5 when no momentum-transfer cuts are made.

[17] The prescription suggested by L. Stodolsky, Phys. Rev. Letters 18, 973 (1967), leads to a calculated curve which is nearly indistinguishable from a Deck-effect calculation according to Stodolsky.

[18] Stodolsky, Ref. 17.

[19] R. T. Deck, Phys. Rev. Letters 13, 169 (1964).

[20] To distinguish the two protons in the final state, the following notation is used: p_1 is the proton which combined with the π^+ gives an effective mass closer to the Δ^{++} than the other proton designated as p_2. As the two invariant masses $p_1\pi^+$ and $p_2\pi^+$ are generally very different, usually only one combination per event, i.e., $p_1\pi^+\pi^-$, will contribute to the $p\pi^+\pi^-$ spectrum below 2.0 GeV as seen in Fig. 1. Thus $p_1\pi^+\pi^-$ is almost always the lower mass $p\pi^+\pi^-$ combination.

INTERFERENCE ANALYSIS OF THE $K^*(1400)$†

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A study of the $K^+\pi^-$ decay mode of the $K^*(1400)$ produced with an N^{*++} has been made using the reaction $K^+p \to K^+\pi^-\pi^+p$ at 5.5 BeV/c. We have fitted the $K^*(1400)$ angular distributions using a model involving interference between 1^- and 2^+ $K^+\pi^-$ states. In this model a considerable amount of 1^- is needed in the $K^*(1400)$ mass region, suggesting that there is a $J^P = 1^-$ resonance under the $K^*(1400)$. Such a $J^P = 1^-$ resonance could be the first daughter of the $K^*(1400)$.

The analysis of high-energy interactions composed of two final particles of which one or both are resonances is complicated by the presence of nonresonant background. The situation can be remedied to a certain extent by assuming that the background, as estimated from mass regions bordering the resonance, may be directly subtracted from the resonance data.[1] This procedure fails in cases where the nonresonant background and the resonance interfere. An example of such an interference is the observation of a backward-forward asymmetry in the decay of the $K^*(890)$ in the process $K^+p \to K^{*0}\Delta^{++}$.[2] This asymmetry is an important aspect of work on a $K\pi$ phase-shift analysis.[3] However, the nonzero value of $\mathrm{Re}\rho_{10}$ [observed in $K^*(890)$ decay] makes apparent the need for more than single π exchange in $K^{*0}\Delta^{++}$ production.[4] $\mathrm{Re}\rho_{10}$ not equal to zero can be achieved by more complicated exchanges or by using an absorptive pion-exchange model.[5,6] We have also found that in our $K^*(1400)\Delta^{++}$ sample, the $K^*(1400)$ decay exhibits characteristics which indicate more than one spin and parity is in the $K\pi$ system and other than π-type exchanges are present. Consequently, we have made an analysis of the $K^*(1400)$ region taking into account both the above effects. This analysis leads in a plausible way to evidence for a $J^P = 1^-$-type structure in the $K^*(1400)$ mass region as well as the presumed $J^P = 2^+$ $K^*(1400)$.

The data are taken from a 3.3-event/μb K^+p exposure at 5.5 BeV/c taken in the Brookhaven National Laboratory 80-in. bubble chamber.

We have examined the properties of the $K^+\pi^-$ system in the reaction

$$K^+p \to K^+\pi^- N^{*++}$$
$$\hookrightarrow p\pi^+, \qquad (1)$$

where the presence of an N^{*++} in an event is defined by the $p\pi^+$ mass being in the interval 1150 to 1340 MeV. In Fig. 1 the $K^+\pi^-$ mass distribution is presented for all events of Reaction (1), and also for the subsample of these events which have $-t$, the square of the four-momentum transfer from the initial proton to the final N^{*++}, in the interval 0.2 to 0.5 (BeV/c)^2. The $K^*(890)$ and $K^*(1400)$ peaks are clearly seen in both histograms. Furthermore, this momentum-transfer cut greatly enhances the apparent signal-to-background ratio in the $K^*(1400)$ region. It is evident from these mass distributions and from momentum-transfer distributions (not shown) that the $K^*(1400)$ is produced at higher momentum transfer than the $K^*(890)$.[8] To utilize the relatively clean $K^*(1400)$ signal found above, we shall limit our analysis to events of the type

$$K^+p \to K^+\pi^- N^{*++}, \quad 0.2 < \Delta^2 < 0.5\ (\mathrm{BeV}/c)^2,$$

and we shall refer to this class of events as Reaction (2) throughout the remainder of this paper.

An examination of the decay properties of the N^{*++} indicates that vector exchange is not enhanced in the $K^*(1400)$ mass region and is relatively small from 1270 to 1570 MeV. However, that some nonzero spin exchange is necessary is found from examination of the $K^+\pi^-$ system. It seems natural to assume that pion (zero-spin) ex-