UR-511 UMBC-74-19 COO-3065-104

Production of Δ(1236) in pp Collisions at High Energies*

J. P. Baton†, C. Bromberg, T. Ferbel, T. Jensen,

R. Schindler‡ and P. Slattery

University of Rochester

Rochester, New York 14627
Contract AT(11-1)-3065

and

A. A. Seidl and J. C. Vander Velde

University of Michigan

Ann Arbor, Michigan 48104

January 3, 1975

Based on data obtained from exposures of the Fermilab 30-inch bubble chamber, we present a comparative study of inclusive $\Delta^{++}(1236)$ production in pp collisions at 102 GeV/c and 400 GeV/c. We observe that, to better than 10% accuracy, the invariant cross section for $\Delta^{++}(1236)$ production for $|t| < 0.6$ GeV^2 and $|x| > 0.7$ does not depend on energy. A comparison of the observed properties of the neutral baryon system produced in association with the $\Delta^{++}(1236)$ and the known characteristics of π^-p collisions reveals a remarkable similarity between the properties of these two neutral multiparticle systems.

*Research supported by the U.S.Atomic Energy Commission. Computing funds at Rochester are provided by the University.

†On leave from C.E.N., Saclay, France.

‡Presently at Dept. of Physics, Stanford University, Stanford, Calif.

The characteristics of inclusive Δ(1236) production at high energies have recently been studied for pp collisions at 303 GeV/c[1] and preliminary results have been reported at 205 GeV/c[2] and at 69 GeV/c[3]. Here we present an investigation of the energy dependence and other hitherto unstudied properties of the reaction:

$$pp \to \Delta^{++}(1236) + X^0 \qquad (1)$$

where X^0 represents anything accompanying the $\Delta^{++}(1236)$.

The data are from a 33,000 picture exposure of the Fermilab 30-inch bubble chamber to 102 GeV/c protons and from a 19,000 picture exposure at 400 GeV/c[4]. In both experiments the beam transmitted to the bubble chamber had the same momentum as the extracted proton beam from the main ring and, consequently, beam-like background was negligible.

We measured all charged tracks for a sample of 3000 events and 2200 events at 102 GeV/c and 400 GeV/c, respectively. The procedures used for proton identification have been described elsewhere.[4],[5] In this paper we will be concerned with $\Delta^{++}(1236)$ production in the backward hemisphere of the center of mass, and, consequently, to avoid biasing this sample of data through our imposed scanning criterion used to select protons, we will restrict our consideration to events which have π^+p invariant masses (M_Δ) in the 1.12 GeV to 1.32 GeV interval and have low values for the squares of four-momentum transfer between target proton and the Δ^{++} ($|t_\Delta| < 0.6$ GeV^2). With these cuts on M_Δ and t_Δ, we retain for further study of Reaction (1) 160 events and 119 events at 102 GeV/c and 400 GeV/c, respectively.

Figure 1(a) displays the π^+p mass spectrum for the selected

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data samples. At both beam energies, a clear enhancement is observed in the π^+p mass at the position of the $\Delta^{++}(1236)$. The cross section for $\Delta^{++}(1236)$ production for $|t_\Delta| < 0.6$ GeV^2 is observed to be, to within 10% statistical accuracy, independent of beam momentum between 102 GeV/c and 400 GeV/c. A similar plot of the π^+p mass spectrum (i.e., for the reaction $pp \to (\pi^-p) + X^{++}$, which is not shown) exhibits the presence of a far weaker signal at the $\Delta^0(1236)$, consistent with the production ratio of $\frac{1}{9}$ for the relative cross sections Δ^0/Δ^{++}, expected if inclusive Δ production proceeds through $I = 1$ exchange in the t-channel. (The cross section for production of np systems outside of the $\Delta(1236)$ range is the same for π^+p as for π^-p pairs.) The t_Δ distributions for Reaction (1) at 102 GeV/c and at 400 GeV/c are shown in Fig. 1(b). Again, within statistical uncertainty, the cross sections at the two energies appear to have the same normalizations and shapes in t_Δ.

The mass of the system recoiling from the $\Delta^{++}(1236)$ does not display the sort of low-mass enhancement observed in the reaction $pp \to p + X^+$ for the X^+ system[4]. In fact, the mass distribution of the X^0 in Reaction (1) is quite featureless. This result is displayed in the x-distribution of the $\Delta^{++}(1236)$ in Reaction (1), as shown in Fig. 1(c). (The x variable is defined to take account of the non-asymptotic nature of Fermilab energies: $x_\Delta = p_L^*/\left(\frac{[s + (M_\Delta + m)^2][s - (M_\Delta - m)^2]}{4s}\right)^{\frac{1}{2}}$, with m representing the proton mass, s the square of the energy in the center of mass system, and p_L^* the longitudinal momentum of the Δ.) The invariant x-spectrum of the $\Delta^{++}(1236)$, integrated over our t_Δ range is also independent of incident momentum, that is, it is observed to

"scale", within statistical uncertainty, for $x_\Delta < -0.7$. Furthermore, there does not appear to be any significant variation in the transverse-momentum spectrum of the Δ as a function of x_Δ or s (the p_T distribution is approximately of the form $\exp(-6p_T^2)$ for $x_\Delta < -0.7$). Our data are too meager to warrant a detailed triple Regge analysis of Reaction (1),[6] however, it appears that pion exchange alone may not account for all Δ production at large $|x_\Delta|$.[7]

In Fig. 2 we display the mean charged-particle multiplicity ($\langle n \rangle_{X^0}$) of the X^0 system associated with $\Delta^{++}(1236)$ production as a function of $M^2_{X^0}$. We also show the variation of the Mueller f_2 moment ($\langle n^2 \rangle - \langle n \rangle^2 - \langle n \rangle$) with $M^2_{X^0}$. The data at 102 GeV/c and at 400 GeV/c are in good agreement, as was the case for an analogous comparison in $pp \to p + X^+$.[8] The smooth curves represent the variation of the same parameters in π^-p collisions as a function of s (i.e., $\pi^-p \to$ Anything, where Anything includes the elastic channel, examined at the square of the energy in the π^-p center of mass (s) corresponding to $s = M^2_{X^0}$)[9]. The low-order charged-particle multiplicity moments in π^-p reactions are seen to be quite consistent with those observed in the "collisions" of the virtual object (or rather objects) N^- with a proton (see the diagram in Fig. 2).

As in our previous investigation[8], we now proceed to examine whether the properties of inclusive pion production in $\bar{N}^-p$ collisions are similar to those observed in π^-p collisions. In particular, we examine the reaction:

$$\bar{N}^-p \to \pi^- + (\text{Anything})^+ \qquad (2)$$

in the rest frame of the X^0 system. Figure 2(c) displays the invariant x distributions of the π^- in Reaction (2) for $M^2_{X^0} < 50$ GeV^2. The usual t-channel direction is chosen as the collision axis for the π^-p objects. Thus, positive x_{π^-} corresponds to emission along the π^- "direction" (opposite to the incident proton) in the X^0 rest frame. The x variable is defined as: $x_{\pi^-} = p_L/[\frac{(M^2_{\Delta^0} - (m + \mu_\pi)^2)(M^2_{X^0} - (m - \mu_\pi)^2)}{4M^2_{X^0}}]^{\frac{1}{2}}$, where p_L is the longitudinal momentum of the π^- in the X^0 rest frame measured along the π^- direction, μ_π is the pion mass, and m is the mass of the proton. (The data at 400 GeV/c for $M^2_{X^0} < 50$ GeV^2 are too meager to permit a meaningful analysis. For comparison we give the x distribution for π^- production in π^-p collisions at $s = 30$ GeV^2 [10]. Normalizations are chosen so that the integrals of the distribution in Fig.2(c) yield the $\langle n \rangle$ values given in Fig. 2(a) (i.e., the elastic channels are included throughout). We note that the character of the results for Reaction (2) is very similar to what is observed in real π^-p data. The asymmetry in the distributions about $x = 0$ is particularly noteworthy. The peak near $x_{\pi^-} = +1$, which is analogous to real π^+p elastic scattering, is derived almost entirely from the four-pronged events of Reaction (1), and indicates the presence of low-mass ($\pi^-\Delta^{++}$) production.[11]

Finally, we have examined (Table I) the angular moments of the $\Delta^{++}(1236)$ decay in the Gottfried-Jackson frame (t_Δ - channel) for $x_\Delta < -0.7$.[12] The results are similar to those obtained at lower energies, for data involving $\Delta(1236)$ production in exclusive reactions where π-exchange is thought to dominate.[13] The large values of $\langle Y^0_2 \rangle$ indicate a preference for $|J_z| = \frac{1}{2}$ spin alignment in the Δ decay, consistent with reactions involving π-exchange.

In conclusion, we have examined inclusive $\Delta(1236)$ production in pp collisions at 102 GeV/c and at 400 GeV/c. We find that the cross sections for Δ production (i.e., M_Δ 1.12 GeV to 1.32 GeV) for $x < -0.7$ and $|t| < 0.6$ GeV^2 are 1.43 ± 0.10 mb and 1.36 ± 0.14 mb at 102 GeV/c and 400 GeV/c, respectively. These cross sections thus appear to be independent of s. Also, Δ production appears to scale in x between 102 GeV/c and 400 GeV/c. And, finally, the internal properties of the system produced in association with the Δ are remarkably similar to those expected on the basis of the exchange of a virtual π^- meson which subsequently interacts with the incident proton. The latter result is analogous to our findings in a previous study of the reaction $pp \to p + X^+$.[8]

We thank E. Berger, R. Field, G. Fox and C. Quigg for discussions. We also acknowledge the help of D. Cohen, D. Chaney and J. M. Cooper in the analysis of the data. Finally, we thank the Directorate and the members of the Neutrino Laboratory at FNAL for their encouragement and help with the bubble chamber exposures.

TABLE I

$\Delta^{++}(1236)$ Decay Moments in the t-channel for $x_\Delta < -0.7$ and $|t_\Delta| < 0.6$ GeV^2

	102 GeV/c	400 GeV/c
$\langle Y^0_1 \rangle$	0.094 ± 0.025	0.007 ± 0.032
$\langle \mathrm{Re} Y^1_1 \rangle$	0.003 ± 0.016	−0.044 ± 0.020
$\langle Y^0_2 \rangle$	0.065 ± 0.024	0.094 ± 0.028
$\langle \mathrm{Re} Y^1_2 \rangle$	−0.017 ± 0.018	−0.019 ± 0.023
$\langle \mathrm{Re} Y^2_2 \rangle$	0.009 ± 0.016	0.053 ± 0.017

References

1. F. T. Dao et al, Phys. Rev. Lett. 30, 34 (1973).
2. N. Derrick et al, Bull. Am. Phys. Soc. 19, 588 (1974) and report in preparation.
3. B. Bialkowska et al, France-USSR Collaboration Report M-11 (1974).
4. J. Chapman et al, Phys. Rev. Lett. 32, 257 (1974).
5. A particle was labeled a proton if the positive track in question had a laboratory momentum less than 1.2 GeV/c and an ionization consistent with a proton interpretation. These requirements are equivalent to selecting an unbiased sample of produced protons with transverse momenta $p_T \leq 0.8$ GeV/c and $x_p < -0.6$. The unbiased region of Reaction (1) for our chosen selection criteria corresponds to $M(\pi + p) < 1.32$ GeV, $x_\Delta < -0.7$ and $|t_\Delta| < 0.6$ GeV^2.
6. See, for example, R.Field and G.Fox, Caltech Report CALT-68-434 (1974) and references given therein.
7. We thank R. Field for the private communication of his calculations.
8. J. P. DeBrion et al, Phys. Letters B52, 477 (1974).
9. Compilation of E. Bracci et al, CERN/HERA 72-1 (1972).
10. Compilation of M. E. Law et al, LBL-80 (1972).
11. The four-pronged events are dominated by the $pp\pi^+\pi^-$ final state, in which case the usual Deck diagram can be thought of as concurrently responsible for low-mass $\pi^-\Delta^{++}$ diffractive excitation and for the forward peak in Fig. 2(c). We thank M. Jacob for a private communication on this point.
12. For $x_\Delta < -0.7$ there is no bias in the Δ decay angles (see footnote 5).
13. See, for example, references given in refs. (1) and (3).

Figure Captions

1. The mass of π^+p systems produced at $|t| < 0.6$ GeV^2 is given in (a). Distributions in t and x of $\Delta^{++}(1236)$ produced in Reaction (1) appear in (b) and (c), respectively. (Both x_{min} and t_{min} are defined to be positive quantities.)

2. The total average charged-particle multiplicity and the f_2 moment of the X^0 system are displayed as a function of $M^2_{X^0}$ in (a) and (b), respectively. The smooth curves are for π^-p data corresponding to $s_{\pi^-p} = M^2_{X^0}$. (c) Inclusive π^- production in π^-p collisions is compared to observed characteristics of π^-p "collisions" shown for two regions of $M^2_{X^0}$.

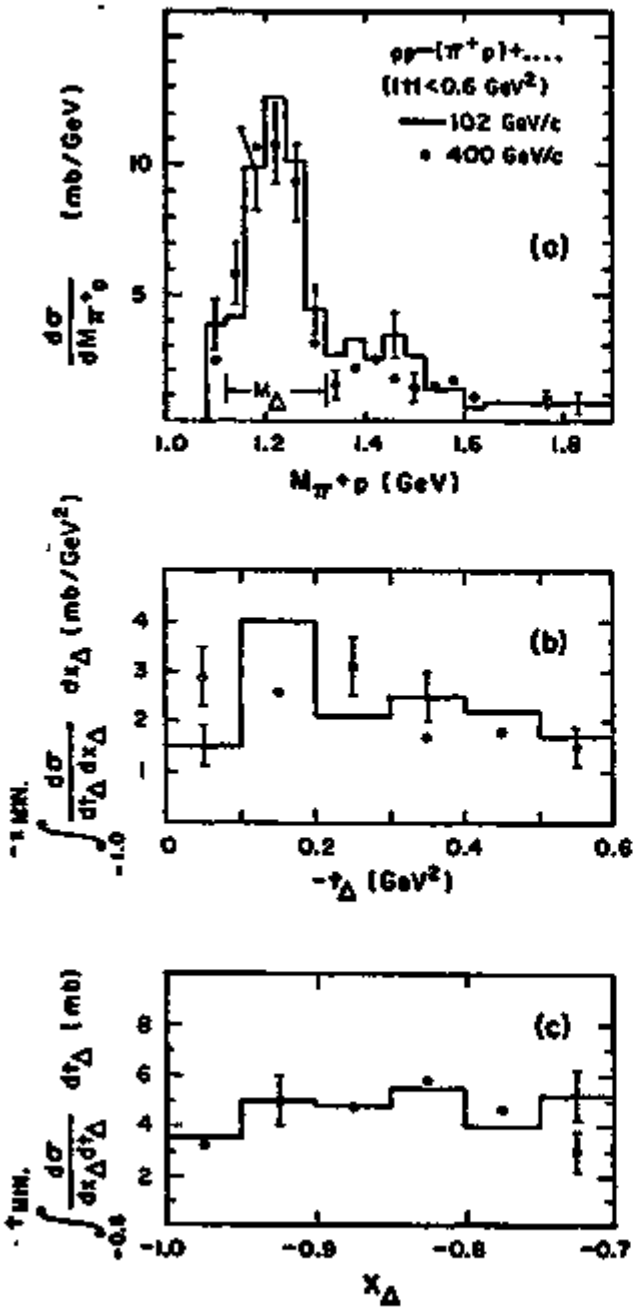
pp→(π⁺p)+....
(|t|<0.6 GeV²)
102 GeV/c
400 GeV/c
(a)
dσ/dM_π⁺p (mb/GeV)
M_Δ
M_π⁺p (GeV)
(b)
dσ/dt_Δ dx_Δ (mb/GeV²)
-t_Δ (GeV²)
(c)
dσ/dx_Δ dt_Δ (mb)
x_Δ

Fig. 1

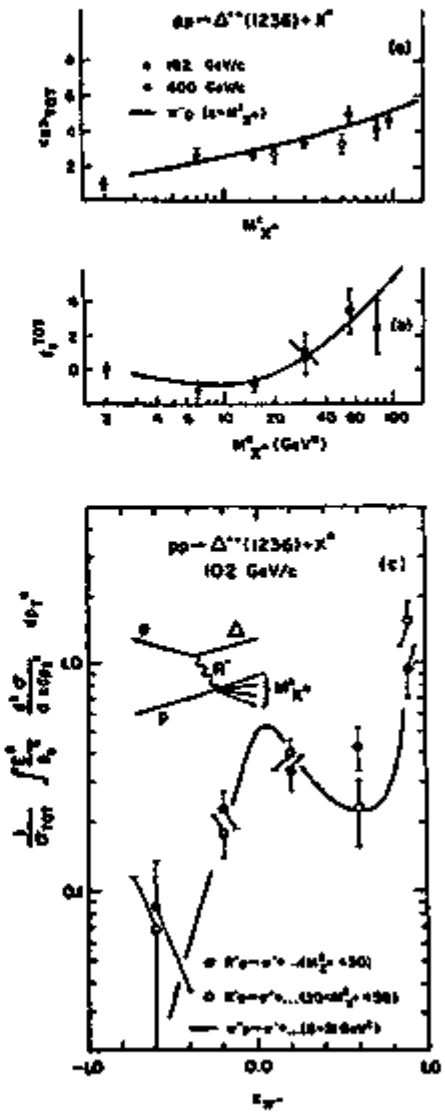
pp→Δ⁺⁺(1236)+X⁻
102 GeV/c
400 GeV/c
(a)
(b)
(c)

Fig 2