New York, 1972).

[5]P. L. Jain, M. Kazuno, and B. Girard, Phys. Rev. Lett. 32, 1460 (1974), and to be published.

[6]P. L. Jain, M. Kazuno, B. Girard, and Z. Ahmad, Phys. Rev. Lett. 32, 797 (1974); J. E. Butt and D. T. King, Phys. Rev. Lett. 31, 904 (1973).

[7]J. Böhm, A. Mátlová, J. Žáček, and V. G. Grishin, Nucl. Phys. B32, 632 (1971); R. L. Kinzer and J. R. Burwell, Phys. Rev. Lett. 20, 1050 (1968), and references therein.

[8]This was estimated from a study of the opening-angle distribution between the positive and negative tracks. Direct-pair production has a sharp peak at zero degrees while hadron production (with both tracks having momentum less than 5 GeV/c) occurs predominantly at large angles.

[9]The total production rate of 1.63×10^{-4} cm^{-1} corresponds to a cross section for the neon-hydrogen mixture of 4.8 mb. However, since direct-pair production is approximately proportional to Z^2, we are essentially measuring production from neon in this experiment. The cross section for direct-pair production from neon alone is 25 mb.

[10]This ignores direct-pair production from atomic electrons. We know of no calculation that properly takes this into account, but, guided by calculations done for γ-ray pair production, we estimate that this would increase the theoretical prediction by about 10%.

[11]Although there are no free parameters, Ternovskii's calculation does incorporate some model-dependent features such as using the Thomas-Fermi model to estimate the effect of electron shielding.

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

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We present a comparative study of inclusive $\Delta^{++}(1236)$ production in pp collisions at 102 and 400 GeV/c. To better than 10% accuracy the invariant $\Delta^{++}(1236)$ cross section does not depend on energy. A remarkable similarity is observed between the properties of the neutral-baryon system produced in association with the $\Delta^{++}(1236)$ and the known characteristics of π^-p collisions.

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

$$p+p\rightarrow\Delta^{++}(1236)+X^0, \tag{1}$$

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

The data are from a 33 000-picture exposure of the Fermilab 30-in. 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, beamlike background was negligible.

We measured all charged tracks for a sample of 3000 and 2200 events at 102 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- 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 and 119 events at 102 and 400 GeV/c, respectively, corresponding to cross sections of 1.65 ± 0.13 and 1.59 ± 0.15 mb.

Figure 1(a) displays the π^+ mass spectrum for the selected data samples. At both beam energies, a clear enhancement is observed in the π^+p

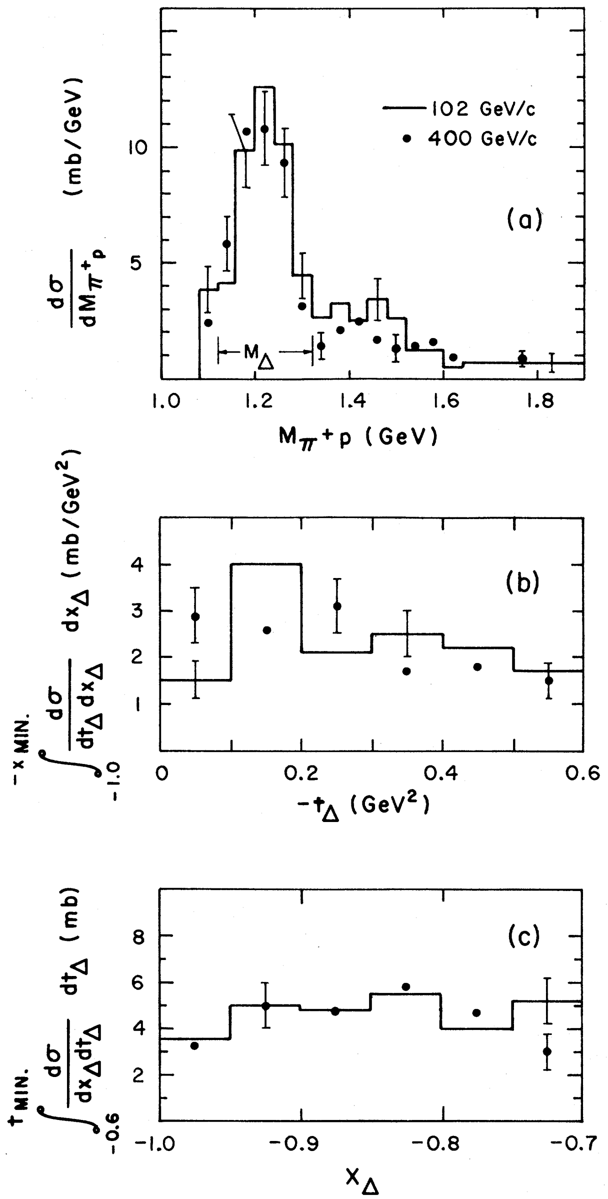

FIG. 1. The mass of π^+p systems produced at $|t| < 0.6$ GeV^2 is given in (a). Distributions in t and x of $\Delta^{++}(1236)$ produced in Reaction (1) appear in (b) and (c), respectively. (Both $x_{\min}$ and $t_{\min}$ are defined to be positive quantities.)

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 and 400 GeV/c. A similar plot of the π^-p mass spectrum [i.e., for the reaction $p+p \to (\pi^- + p) + X^{++}$, 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 πp 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 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 $p+p \to p + X^+$ 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 nonasymptotic nature of Fermilab energies:

$$x_\Delta = p_l^*\left(\frac{[s-(M_\Delta+m)^2][s-(M_\Delta-m)^2]}{4s}\right)^{-1/2},$$

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 $\exp(-6 \times p_T^2)$ 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 ($\langle n \rangle_{\text{tot}}$) of the X^0 system associated with $\Delta^{++}(1236)$ production as a function of $M_{X^0}^2$. We also show the variation of the Mueller f_2 moment ($\langle n^2 \rangle - \langle n \rangle^2 - \langle n \rangle$) with $M_{X^0}^2$. The data at 102 and at 400 GeV/c are in good agreement, as was the case for an analogous comparison in $p+p \to p + X^+$.[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 $s = M_{X^0}^2$].[9] The low-order charged-particle multiplicity moments in π^-p reactions are seen to be quite consistent with those

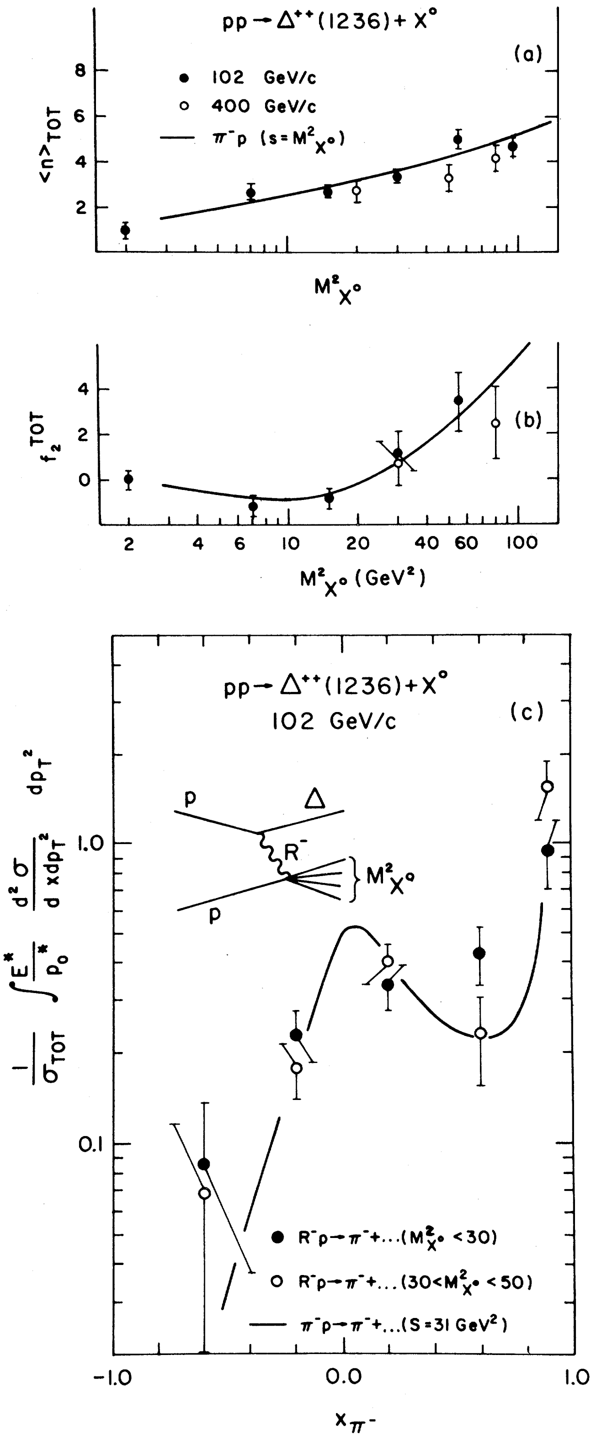

FIG. 2. The total average charged-particle multiplicity and the f_2 moment of the X^0 system are displayed as a function of $M_{X^0}{}^2$ in (a) and (b), respectively. The smooth curves are for π^-p data corresponding to $s_{\pi^-p}=M_{X^0}{}^2$. (c) Inclusive π^- production in π^-p collisions is compared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

observed in the "collisions" of the virtual object (or rather objects) R^- 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 R^-p collisions are similar to those observed in π^-p collisions. In particular, we examine the reaction

$$R^- + p \to \pi^- + (\text{anything})^+ \qquad (2)$$

in the rest frame of the X^0 system. Figure 2(c) displays the invariant x distributions of the π^- in Reaction (2) for $M_{X^0}{}^2 < 50\ \text{GeV}^2$. The usual t-channel direction is chosen as the collision axis for the R^-p objects. Thus, positive x_{π^-} corresponds to emission along the R^- "direction" (opposite to the incident proton) in the X^0 rest frame. The x variable is defined as

$$x_{\pi^-} = p_l \left(\frac{[M_{X^0}{}^2-(m+\mu_\pi)^2][M_{X^0}{}^2-(m-\mu_\pi)^2]}{4M_{X^0}{}^2}\right)^{-1/2},$$

where p_l is the longitudinal momentum of the π^- in the X^0 rest frame measured along the R^- direction, μ_π is the pion mass, and m is the mass of the proton. (The data at 400 GeV/c for $M_{X^0}{}^2 < 50\ \text{GeV}^2$ are too meager to permit a meaningful analysis.) For comparison we give the x distribution for π^- production in π^-p collisions at $s \approx 30\ \text{GeV}^2$.[10] Normalizations are chosen so that the integrals of the π^- distributions in Fig. 2(c) yield one half of the $\langle n\rangle$ values given in Fig. 2(a) (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 $\langle Y_2{}^0\rangle$ 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 and

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
$\langle Y_1^0 \rangle$	0.094 ± 0.025	0.007 ± 0.031
$\langle \mathrm{Re} Y_1^1 \rangle$	0.003 ± 0.016	-0.044 ± 0.020
$\langle Y_2^0 \rangle$	0.065 ± 0.024	0.094 ± 0.028
$\langle \mathrm{Re} Y_2^1 \rangle$	-0.017 ± 0.018	-0.019 ± 0.023
$\langle \mathrm{Re} Y_2^2 \rangle$	0.009 ± 0.016	0.053 ± 0.017

400 GeV/c. We find that the cross sections for Δ production (i.e., M_Δ in the range 1.12 to 1.32 GeV) for $x < -0.7$ and $|t| < 0.6$ GeV^2 are 1.43 ± 0.12 and 1.36 ± 0.14 mb at 102 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 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 $p + p \to p + X^+$.[8]

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[1] F. T. Dao *et al.*, Phys. Rev. Lett. 30, 34 (1973).

[2] M. Derrick *et al.*, Bull. Amer. Phys. Soc. 19, 588 (1974), and to be published.

[3] H. Bialkowska *et al.*, Université de Paris–Centre d'Etudes Nucléaires de Saclay–Joint Institute for Nuclear Research, Serpukhov–Institute for High Energy Physics, Alma Ata (France-U.S.S.R. Collaboration), Joint Report No. M-11, 1974 (unpublished).

[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 $p_T \lesssim 0.8$ 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, California Institute of Technology Report No. CALT-68-434, 1974 (unpublished), and references given therein.

[7] We thank R. Field for the private communication of his calculations.

[8] J. P. DeBrion *et al.*, Phys. Lett. B52, 477 (1974).

[9] Compilation of E. Bracci *et al.*, CERN Report No. CERN/HERA 72-1, 1972 (unpublished).

[10] Compilation of M. E. Law *et al.*, LBL Report No. LBL-80, 1972 (unpublished).

[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 Ref. 5).

[13] See, for example, references given in Refs. 1 and 3.