G. Paulikas, J. A. Simpson, and S. Singer for permission to quote their preliminary satellite proton and α results, to W. R. Giard, M. McConnell, and G. E. Nichols for experimental assistance, and to M. Saltmarsh and A. van der Woude for permission to quote joint work prior to publication.

*Work supported by The National Aeronautics and Space Administration under Contract No. NAS 9-11468.

[1]More detailed descriptions of the experiments are given by R. L. Fleischer and H. R. Hart, Jr., in National Aeronautics and Space Administration Apollo-16 Preliminary Science Report, 1972 (unpublished); P. B. Price *et al.*, *ibid.*; R. M. Walker *et al.*, *ibid.*

[2]R. L. Fleischer, P. B. Price, and R. T. Woods, Phys. Rev. 88, 563 (1969).

[3]R. L. Fleischer, P. B. Price, and R. M. Walker, J. Geophys. Res. 70, 1497 (1965).

[4]W. T. Crawford, W. DeSorbo, and J. S. Humphrey, Nature (London) 220, 1313 (1968).

[5]P. B. Price and R. L. Fleischer, Radiat. Eff. 2, 29 (1970).

[6]D. D. Peterson, Rev. Sci. Instrum. 41, 1254 (1970).

[7]L. C. Northcliffe and R. F. Schilling, *Range and Stopping Power Tables for Heavy Ions* (Texas A & M, College Station, Texas, 1970), and Nucl. Data, Sect. B 7, 233 (1970).

[8]H. R. Hart, Jr., M. Saltmarsh, A. van der Woude, and R. L. Fleischer, to be published.

[9]L. H. Aller, *Abundance of the Elements* (Wiley, New York, 1961).

[10]R. L. Fleischer, H. R. Hart, Jr., and G. M. Comstock, Science 171, 1240 (1971).

[11]A. Mogro-Campero and J. A. Simpson, Astrophys. J. 171, L5 (1972).

[12]G. Crozaz and R. M. Walker, Science 171, 1237 (1971).

[13]P. B. Price, I. Hutcheon, R. Cowsik, and D. J. Barber, Phys. Rev. Lett. 26, 916 (1971).

[14]B. Teegarden, T. T. van Rosenvinge, and F. B. McDonald, Goddard Space Flight Center Report No. X-661-72-222 (to be published).

[15]D. L. Bertsch, C. E. Fichtel, C. J. Pellerin, and D. V. Reames, Goddard Space Flight Center Report No. X-662-72-197 (to be published).

[16]D. L. Bertsch, C. E. Fichtel, and D. V. Reames, Astrophys. J. 171, 169 (1972).

[17]A. Unsöld, Phil. Trans. Roy. Soc. London, Ser. A 270, 23 (1971).

[18]S. Biswas and C. E. Fichtel, Space Sci. Rev. 4, 709 (1965).

[19]A. A. Korchak and S. I. Syrovatskii, Dokl. Akad. Nauk. SSSR 122, 792 (1958) [Sov. Phys. Dokl. 3, 983 (1958)].

pp Interactions at 303 GeV/c; Inclusive Measurement of Δ^{++}(1236) Resonance Production*

F. T. Dao,† D. Gordon,† J. Lach,† and E. Malamud†
University of California, Los Angeles, California 90024

and

T. Meyer,‡ R. Poster,‡ P. E. Schlein,‡ and W. E. Slater‡
National Accelerator Laboratory, Batavia, Illinois 60510
(Received 20 November 1972)

We have observed substantial Δ^{++}(1236) production in the inclusive reaction $p+p\rightarrow\Delta^{++}$ + everything at 303 GeV/c ($\sqrt{s}=23.9$ GeV). This process with $t_{p,\Delta}<1.0$ GeV^2 accounts for ~14% of the total pp inelastic cross section. The mean invariant mass of "everything" is ~11 GeV, which implies that the Δ^{++} is usually part of a higher-multiplicity system moving in its hemisphere. The distribution in squared transverse momentum to the Δ^{++} falls off exponentially with a slope of about 12 GeV^{-2}.

In a recent exposure of the National Accelerator Laboratory (NAL) 30-in. hydrogen bubble chamber to a 303-GeV/c proton beam ($\sqrt{s}=23.9$ GeV), a sample of 2245 pp interactions was obtained. A multiplicity study of these events has already been reported.[1]

Despite the large momenta involved in the interactions, particles which travel backward in the pp c.m. system have comparatively low momenta in the laboratory and can be measured and analyzed with conventional film-measuring machines and analysis techniques. In the present work, results are reported on the inclusive reaction

$$p+p\rightarrow\Delta^{++}(1236)+\text{“everything”} \qquad (1)$$

obtained from measurements of all tracks with lab momentum $P_{lab}<1.4$ GeV/c. With this momentum cutoff, full acceptance is obtained for all breakup angles of the $\Delta^{++}(1236)$ when $P_{\Delta^{++}}{}^{\text{lab}} < 1.35$ GeV/c, corresponding to a momentum transfer between target proton and Δ^{++} of $t_{p,\Delta} < 1.0$ GeV^2.

With $P_{\text{lab}} < 1.4$ GeV/c, it is possible to distinguish pions from protons in a nearly ambiguity-free manner.[2] Each event in a reduced fiducial volume sample of 1750 events[3] was examined once by a scanner and once by a physicist, and the curvatures of all tracks in three views compared with a 1.5-GeV/c template[4]; those tracks with greater curvature were measured on image-plane digitizing tables. For these tracks, the measurers also recorded a π-p ionization decision which was subsequently checked by the physicist who examined the event. All measured tracks were passed through the Berkeley program TVGP (three-view-geometry program) to obtain their stereo-reconstructed space angles and momenta.

In the fiducial volume used for these measurements, 806 events were found which contained a proton with $P < 1.4$ GeV/c. Of these, 214 events contained in addition at least one π^+ (166 events had one π^+, 41 had two π^+, and 7 had three π^+ among the tracks measured). The distribution in π^+p invariant mass for these events (all combinations plotted) is shown in Fig. 1(a). A substantial signal for Reaction (1) is seen; the smooth curve is hand drawn to qualitatively represent the non-$\Delta^{++}(1236)$ background. Figure 1(b) is a similar plot of all $p\pi^-$ invariant-mass combinations in the corresponding sample of 187 events with a proton and at least one π^+. Although a small $\Delta^0(1236)$ signal seems to be present, the nearly identical shapes and absolute magnitudes of the non-Δ backgrounds in the two cases is perhaps the more interesting feature of the distributions and further enhances the credibility of the Δ^{++} signal.

Figures 1(c) and 1(d) show the effects of the selection $t_{p,\Delta} < 1.0$ GeV^2. Although the background is considerably reduced, the Δ^{++} signal is hardly diminished, indicating that it is confined almost entirely to low $t_{p,\Delta}$. We henceforth select events with $1.16 < m_{\pi^+p} < 1.32$ GeV and $t_{p,\Delta} < 1.0$ GeV^2, and summarize some of the properties of Reaction (1). 89 events have one π^+p combination and 8 events have two combinations which satisfy this selection. At the present level of statistics, there is no significant difference between the multiplicity distribution of these events and that of the total data sample.[1]

We find a cross section for Reaction (1) with $t_{p,\Delta} < 1.0$ GeV^2 of 4.3 ± 0.5 mb, after multiplying

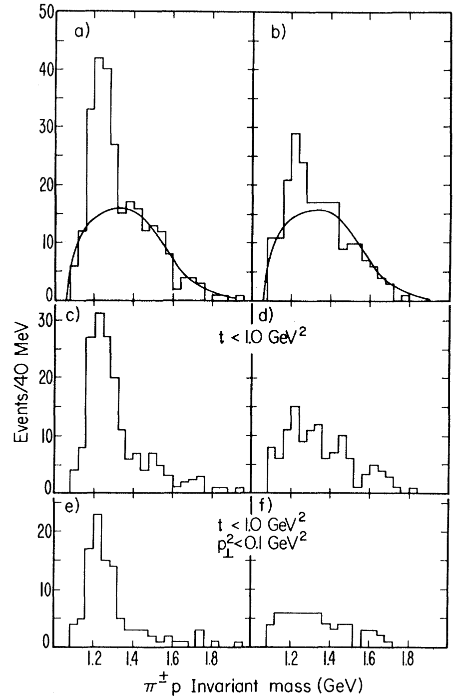

FIG. 1. (a), (c), (e) π^+p and (b), (d), (f) π^-p invariant-mass spectra. (a), (b) All combinations with $P_{\text{lab}} < 1.4$ GeV/c for both p and π. (c), (d) Same, but with the additional restrictions that $t_{p,\Delta} < 1.0$ GeV^2. (e), (f) Same, but with additional restrictions that $(P_\perp{}^2)_\Delta < 0.1$ GeV^2. See text for relevant numbers of events and multiple mass combinations. Curves in (a) and (b) are identical and hand drawn to provide an approximate representation of the non-Δ background.

by a factor of 2 to correct for the (symmetric) forward-going Δ^{++}'s which have not been detected (and assuming that simultaneous Δ^{++} production in both hemispheres is a small fraction of the total). This value may be compared with the corresponding value determined at 6.6 GeV/c. Colton and co-workers[5-8] have measured cross sections for all processes of the type $p+p \to \Delta^{++} + \text{nucleon} + n\pi$, where $n = 0, 1, 2$, and find $\sigma = 9.2$ mb; the states with $n \geq 3$ are estimated to contribute only an additional ~0.8 mb, yielding $\sigma_{\text{total}} \sim 10 \pm 1$ mb. Thus the cross section for Reaction (1) drops only about a factor of 2 between 6.6 and 303 GeV/c.

We now turn to a discussion of the Δ^{++} distributions in the variables $X = 2P_\parallel/\sqrt{s}$ and $P_\perp{}^2$, displayed in Fig. 2, where the momentum subscripts refer to the components in the c.m. system both parallel and perpendicular to the beam momentum. The kinematics are summarized in Fig. 2(e) which shows, in the X-$P_\perp{}^2$ plane, contours of

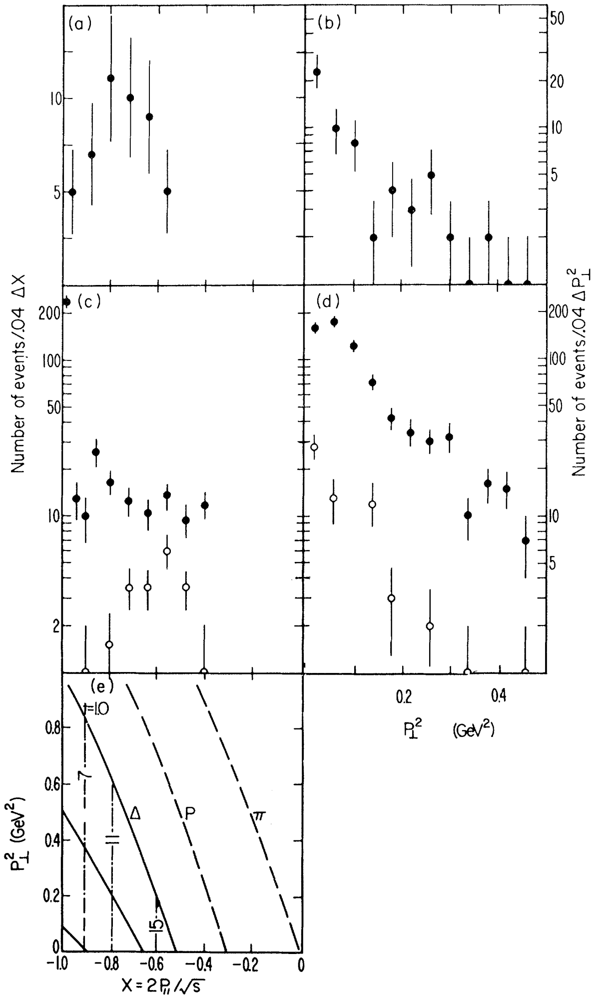

FIG. 2. (a) X_Δ distribution of the Δ^{++} for the selection $(P_\perp^2)_\Delta < 0.1\,\mathrm{GeV}^2$; (b) $(P_\perp^2)_\Delta$ of the Δ^{++} for $X_\Delta < -0.6$; (c), (d) same, but for all protons (filled circles) and for protons coming from Δ^{++} decay (unfilled circles). The selections made in (c) and (d) are $(P_\perp^2)_p < 0.1\ \mathrm{GeV}^2$ and $X_p < -0.4$, respectively; in (d) the missing unfilled-circle points are zero and do not appear on the plot. (e) Kinematic curves. Dashed lines, contours of 1.4 GeV/c lab momentum for π's and p's. Solid curves, contours of Δ^{++} lab momentum which correspond to $t_{p,\Delta} = 1.0$, 0.5, and 0.1 GeV^2, respectively (reading from top to bottom). Dash-dotted curves, lines of constant missing mass to the Δ^{++} [mass of "everything" in Eq. (1)] of 7, 11, and 15 GeV, respectively (reading from left to right).

$t_{p,\Delta}$ (solid lines) and mass of "everything" (dash-dotted lines) for Reaction (1). The unbiased Δ^{++} events in our sample thus lie to the left of the $t = 1.0$ line. Shown as dashed lines in the figure are contours of constant $P_{\mathrm{lab}} = 1.4$ GeV/c for protons and π's, relevant to our single-particle proton and π distributions, the complete set of which shall be published elsewhere.

The distribution in X_Δ [Fig. 2(a)] is seen to display a broad maximum centered at about $X_\Delta \sim -0.8$ (a less stringent cut on $P_\perp^2$ leads to the same type of distribution but with smaller errors). On a missing-mass (m_X) scale, the peak occurs at about ~10–11 GeV. Such large missing-mass values are likely if constituents of the "everything" system in Reaction (1) travel in the same hemisphere as the Δ^{++}. Because of the broad range in missing mass, the distribution in $t_{p,\Delta}$ is not, in itself, very transparent. The minimum value in $t_{p,\Delta}$ depends on m_X and varies over a correspondingly large range as can be seen in Fig. 2(e). More germane are the variables $t' = t - t_{\mathrm{min}}$ or $P_\perp^2$; for the small c.m. production angles encountered here, these variables are related by $t' = P_\perp^2/X$. The $(P_\perp^2)_\Delta$ distribution shown in Fig. 2(b) for $X_\Delta < -0.6$ is seen to drop off exponentially with a slope of about 12 GeV^{-2} (because $\langle X\rangle \sim 0.75$, the exponent in the t' distribution is ~9). We thus find that $\Delta^{++}(1236)$ production takes place predominantly at small t' (or $P_\perp^2$), independently of X_Δ (or missing mass) in Reaction (1).

The distributions in X_p and $(P_\perp^2)_p$ of the protons which come from Δ^{++} decay are shown in Figs. 2(c) and 2(d), respectively. In each case, the distributions are compared with the corresponding distributions for *all* protons. It can be seen, for example, that whereas protons with large $|X|$ do not contribute to Δ^{++} production, at $|X| \sim 0.6$, 50% (or more) of all protons come from the decay of $\Delta^{++}(1236)$. The $(P_\perp^2)_p$ distribution for protons from Δ's falls off more sharply than does the distribution for all protons. This is kinematically related to the observed $(P_\perp^2)_\Delta$ distribution and the (relatively) low momentum in $\Delta(1236)$ decay.

Finally, we consider the spin alignment of the Δ^{++}. The results can be expressed in terms of the Y_2^0 spherical-harmonic moment of the Δ^{++} breakup angular distribution in its c.m. system. For a spin-$\frac{3}{2}$ particle, $-0.126 \leq \langle Y_2^0\rangle \leq +0.126$, where the lower (upper) limit corresponds to pure $m = \pm\frac{3}{2}$ ($\pm\frac{1}{2}$) alignment. We find in the s- and t-channel frames the values $\langle Y_2^0\rangle = 0.111 \pm 0.030$ and 0.092 ± 0.028, indicating that $m = \pm\frac{1}{2}$ dominates. $\langle Y_1^0\rangle$ is found to be 0.078 ± 0.032 and 0.092 ± 0.031 in the two frames, respectively, similar to that found at lower momenta.[9] The $m \neq 0$ moments $\langle \mathrm{Re}\,Y_1^1\rangle$, $\langle \mathrm{Re}\,Y_2^1\rangle$, and $\langle \mathrm{Re}\,Y_2^2\rangle$, which measure dependence on Treiman-Yang angle,[10] are found to be compatible with zero. Our values of $\langle Y_2^0\rangle$ suggest a somewhat higher degree of alignment of the Δ^{++} than in the π-exchange-dominated Δ^{++} production reactions at lower beam momenta.[9]

We express our appreciation to the NAL operations staff for their invaluable help in securing this exposure. This work would not have been possible without the friendly, dedicated, and careful work of the scanning staff of the NAL film analysis facility. In particular, the members of the UCLA group wish to express their gratitude to this facility and to their colleagues at NAL for the hospitality during the period in which the film was taken and the measurements made.

---

*Accepted without review under policy announced in Editorial of 20 July 1964 [Phys. Rev. Lett. 13, 79 (1964)].

†Work supported by the U. S. Atomic Energy Commission.

‡Work supported by the National Science Foundation under Grant No. GP-33565.

[1]F. T. Dao, D. Gordon, J. Lach, E. Malamud, T. Meyer, R. Poster, and W. Slater, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

[2]The ionization of a 1-GeV/c proton is 2 times minimum; for a 1.5-GeV/c proton it is 1.5 times minimum. Kaons cannot be unabiguously identified over the entire momentum range covered. For this reason and also because the small contamination is not relevant for the present study, some such tracks are arbitrarily included among the pions.

[3]The scanning efficiency is estimated to be better than 99%.

[4]The more restrictive cut of 1.4 GeV/c was later applied in selecting the final data sample in order to ensure a sharp cutoff momentum.

[5]E. Colton, P. E. Schlein, E. Gellert, and G. A. Smith, Phys. Rev. Lett. 21, 1548 (1968).

[6]Z. Ming Ma, G. A. Smith, R. J. Sprafka, E. Colton, and P. E. Schlein, Phys. Rev. Lett. 23, 342 (1969).

[7]E. Colton, P. E. Schlein, Z. Ming Ma, and G. A. Smith, Phys. Rev. D 2, 2108 (1970); E. Colton, private communication.

[8]E. Colton, P. E. Schlein, E. Gellert, and G. A. Smith, Phys. Rev. D 3, 1063 (1971).

[9]See, for example, Ref. 8, or H. H. Bingham, W. M. Dunwoodie, D. Drijard, D. Linglin, Y. Goldschmidt-Clermont, F. Muller, T. Trippe, F. Grard, P. Herquet, J. Naisse, R. Windmolders, E. Colton, P. E. Schlein, and W. E. Slater, Nucl. Phys. B41, 1 (1972).

[10]We use the conventional s- and t-channel coordinate frames, whereby the Δ^{++} direction and the target proton are chosen as the polar axes, respectively, and the y-axis is taken along the normal to the production plane. The $\mathrm{Im}Y_l^m$ moments are thus required to be zero by parity conservation. For $\langle \mathrm{Re}Y_1^1\rangle$, $\langle \mathrm{Re}Y_2^1\rangle$, $\langle \mathrm{Re}Y_2^2\rangle$, we find 0.04 ± 0.02, 0.02 ± 0.02, and 0.02 ± 0.02; and 0.00 ± 0.02, -0.03 ± 0.02, and 0.02 ± 0.02 in the s and t channels, respectively.

ERRATUM

THEORY OF MANY-BODY EFFECTS ON CONDUCTION-ELECTRON SPIN RESONANCE IN A g-ANISOTROPIC METAL. D. R. Fredkin and R. Freedman [Phys. Rev. Lett. 29, 1390 (1972)].

On page 1391 the equations for $\delta E_{\alpha\beta}(k,r)$ and $\chi_-(\omega)$ contain misprints. The equations should read

$$\delta E_{\alpha\beta}(k,r)=a\delta_{\alpha\beta}\,\mathrm{tr}\int\frac{d^3k'}{(2\pi)^3}\delta f(k',r)+b\sigma_{\alpha\beta}\cdot\mathrm{tr}\int\frac{d^3k'}{(2\pi)^3}\sigma\delta f(k',r),$$

i.e., in the second integral $\delta f(k',r)$ should replace $f(k',r)$; and

$$\chi_-(\omega)=\chi_0+\frac{i\omega\nu\mu_B^2}{4}\left\{\frac{\langle g\rangle}{1+B}G_{10}+G_{11}+\left(\frac{\langle g\rangle}{1+B}G_{00}+G_{01}\right)\left[\frac{\langle g\rangle}{1+B}+\left(\frac{1}{\tau_0}-i\omega\frac{B}{1+B}\right)G_{10}\right]\right.$$
$$\left.\times\left[1-\left(\frac{1}{\tau_0}-i\omega\frac{B}{1+B}\right)G_{00}\right]^{-1}\right\},$$

i.e., the exponent -1 should apply only to the last factor in square brackets.