Dr. Haskin's current view of this event favors the interpretation of it as a rare statistical fluctuation in a conventional photon shower initiated in the very thin aluminum case around the emulsion. We are grateful to him for a conversation about it.

[7]Such a bound pole pair would not cause observable ionization as long as the separation is much smaller than 5×10^{-11} cm. Moreover, unless the pole rest mass greatly exceeds 100 BeV, for $\gamma\sim 10^5$ the distance travelled before annihilation would be less than a micron.

[8]We note that it is characteristic of electron-positron production by γ rays that their relative kinetic energy is usually of order m_ec^2. If the pole pairs produced by this same process have a relative kinetic energy Mc^2, then the strong photon emission which accompanies them would be particularly effective in reducing the relative velocity below that needed to escape.

[9]In a perturbation-theory estimate which neglects pole structure, radiation damping, and final-state enhancement, the ratio of pole-pair production cross section to that for e^--e^+ is $(g^2/e^2)^2(m_e/m)^2$, which is indeed of order unity for $M\sim(g^2/\hbar c)m_\pi$. However, there is obviously no reason to consider perturbation theory as a guide since $g^2/\hbar c \gg 1$, and in fact it gives a cross section, near threshold, for pole-antipole production in a two-photon collision which greatly exceeds the unitarity limit.

[10]The energetic photons from annihilation of bound pole pairs would result in anomalous extensive air showers without any appreciable muon or other penetrating component. For reports of such showers see, for example, J. Gawin, J. Hibner, J. Wdowczyk, A. Zawadzke, and R. Maze, in Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965 (The Institute of Physics and The Physical Society, London, 1966), Vol. 2, p. 639.

PHOTOPRODUCTION OF $\pi^-\Delta^{++}(1236)$ FROM HYDROGEN FROM 5 TO 16 GeV*

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The cross section for $\gamma p\to\pi^-\Delta^{++}(1236)$, measured at 5, 8, 11, and 16 GeV from near-zero momentum transfer to -1 GeV^2 (-2 GeV^2 at 16 GeV), rises from small t to a maximum near $-t=m_\pi^2$, then falls as e^{12t} out to $-t\approx 0.2$ GeV^2, after which it becomes roughly equal in slope and magnitude to the single π^+ photoproduction cross section (e^{3t}). At fixed t, the cross section varies as k^{-2}, where k is the laboratory photon energy. The results do not agree well with the simple vector-dominance model.

The differential cross section for

$$\gamma p\to\pi^-\Delta^{++}(1236) \qquad (1)$$

has been measured at 5, 8, 11, and 16 GeV using the Standard Linear Accelerator Center 20-GeV/c spectrometer system.[1] This work extends previous measurements in the few-GeV region.[2]

The apparatus and method are the same as used by Boyarski et al.,[3] with two modifications. First, in addition to the Čerenkov monitor, a secondary-emission quantameter was used to monitor the beam. Except for laboratory angles $\leqslant 1°$, these two monitors could be used simultaneously and provided a cross check of the monitor stability; in general, this stability was found to be about $\pm\frac{1}{2}\%$. These monitors were calibrated against two precision calorimeters which served as absolute standards. The second change was the use of a threshold gas Čerenkov counter to separate the group e,μ,π from K mesons and protons. As before, the pions were then identified by their interaction properties.

To determine the Δ^{++} yield, the 20-GeV/c spectrometer system was used to measure the momentum spectrum of π^- mesons produced in hydrogen by a bremsstrahlung beam. This yield of π^- mesons was determined as a function of missing mass (calculated for $k=E_0$, the bremsstrahlung end-point energy); $\Delta^{++}(1236)$ production should appear as a step in the π^- yield versus missing mass at $M_x^2=1.53$ GeV^2, reflecting the step in the photon spectrum near the end point. The width of the rise of the step is mainly determined by the natural width of the Δ with a small contribution from the experimental resolution. Data were normally taken over the range $1.2 \leqslant M_x^2\leqslant 2.5$ GeV^2.

For process (1) the shape of the Δ was assumed to be given by a Jackson relativistic Breit-Wigner form[4]

$$R(m^2)=\frac{1.13}{\pi}\frac{m_0\Gamma(m)}{(m^2-m_0^2)^2+m_0^2\Gamma^2(m)} \qquad (2a)$$

with

$$\Gamma(m) = \Gamma(m_0)\left(\frac{q}{q_0}\right)^3\left(\frac{am_\pi^{\ 2} + q_0^{\ 2}}{am_\pi^{\ 2} + q^2}\right)\left(\frac{m_0}{m}\right), \tag{2b}$$

where $m_0 = 1.236$ GeV, $\Gamma(m_0) = 0.120$ GeV, $a = 2.2$; q, q_0 are the c.m.-system momentum at masses m, m_0 in the Δ rest system. This shape was cut off at $m = 1.836$ GeV and the factor 1.13 normalizes the integral of $R(m^2)$ to 1. The Breit-Wigner distribution was folded in with the bremsstrahlung spectrum (calculated for a 0.03 X_0 radiator[5]) and with the two-body $\pi\Delta$ phase space.

Various fits were made to the π^- spectra assuming a contribution from Reaction (1) plus a background from one or more of the processes

$$\gamma p \to \rho^0 p, \quad \rho^0 \to \pi^-\pi^+, \text{ rho}, \tag{3}$$

$$\gamma p \to \pi^- + (\pi^+ p), \text{ Drell}, \tag{4}$$

$$\gamma p \to \pi^-\pi^+ p, \text{ phase space}. \tag{5}$$

The contribution from ρ production [Eq. (3)] was calculated using a relativistic Breit-Wigner distribution for the rho meson with a mass of 0.765 GeV and width 0.13 GeV; the production cross section was assumed to have a t dependence of e^{8t} and the ρ to have helicity ± 1 as indicated by experiment.[6] In the simple one-pion exchange (OPE) model of Drell[7] the yield is proportional to $\sigma_{\text{tot}}(\pi^+p)$; to avoid double counting, the contribution of $\Delta(1236)$ was removed from the total cross-section values used in the program. The background from phase space was calculated assuming a yield proportional to the available phase space only.

The fitting program did a least-squares fit to the data, varying the amount contributed by each process included in the hypothesis.[8] Excellent fits to the data were obtained at all energies by attributing the background solely to π^-'s from ρ^0 decay. Adding in other contributions to the background did not cause significant decreases in the χ^2 values, but did cause the uncertainty in the Δ contributions to increase with corresponding random shifts in the fitted cross section. Inclusion of phase-space background in the fits gave phase-space contributions which were small or consistent with zero. Good fits were also obtained by attributing all the background to the Drell mechanism. At 16 GeV the Δ cross sections obtained from the $\Delta+\rho$ fits were almost identical to those from the Δ+Drell fits.[9] Since the photoproduc-

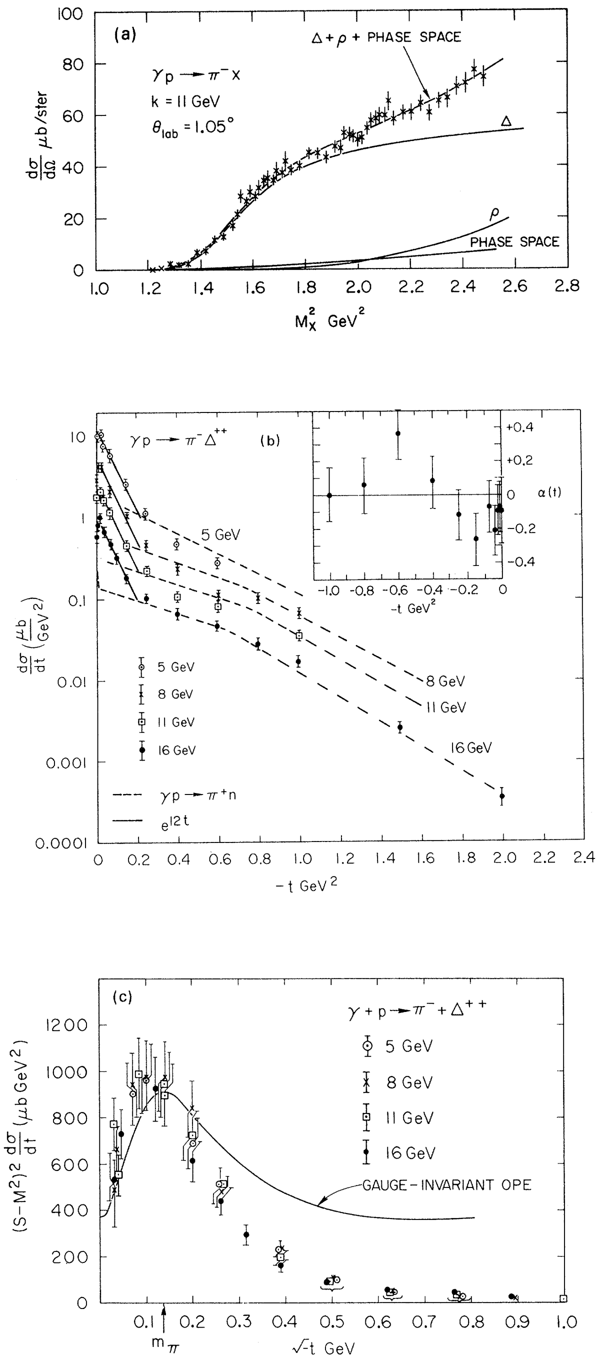

FIG. 1. (a) Fit to the π^- yield. Solid curves give the individual contributions, and the dashed curve is the sum of the solid curves. (b) Differential cross section versus momentum transfer. The dashed lines are smooth curves through the single-π^+ photoproduction data of Ref. 3. The insert shows the Regge parameter α vs t. (c) The small-t cross section on an expanded scale. The curve is the gauge-invariant OPE calculation of Ref. 10.

tion of ρ^0 mesons at high energies has been well established, we consider the $\Delta+\rho$ fits to be the most reliable and have used these fits exclusively to determine the Δ cross sections. Figure 1(a) shows a typical fit to the data using the hypothesis that the π^- yield has contributions from Δ production, ρ production and decay, and phase space. The two background terms contribute very little to the yield in the region of the Δ step. The least-squares fitting program usually gave statistical errors of only a few percent; we have increased these errors to a minimum of 15% to reflect our estimate of the systematic uncertainty in the background calculations. There is in addition an overall normalization uncertainty of about ±10%. The Δ^{++} differential cross sections are listed in Table I.

Figure 1(b) shows the differential cross section for Δ production plotted versus t. The data at all four energies have the same general characteristics—a sharp rise from $|t|$ of 0 to m_π^2, a steep fall approximately as e^{12t} from $|t|$ of m_π^2 to about 0.2 GeV^2, and a change in slope to about e^{3t} for $|t|>0.2$ GeV^2. For $|t|>0.2$ GeV^2 the magnitude as well as the slope of the Δ cross section is roughly the same as that found for $\gamma p\to\pi^+n$. Using the Regge parametrization

$$d\sigma/dt=\beta(t)(s-M^2)^{2\alpha(t)-2}, \tag{6}$$

where s is the square of the total energy in the c.m. system and M is the nucleon mass, we find from the 8-, 11-, and 16-GeV data the values of α shown in the insert in Fig. 1(b). The error bars shown reflect the 15% systematic uncertainty in the cross sections. With some fluctuations, the data are consistent with $\alpha=0$; i.e., Δ^{++} production has the same $1/k^2$ energy dependence of the single-$\pi^\pm$ and K^+ production cross sections.

In Fig. 1(c), $(s-M^2)^2(d\sigma/dt)$ is plotted versus $\sqrt{|t|}$ to display the small-momentum-transfer region better. The cross section rises very rapidly from $|t|_{\rm min}$ to m_π^2, and then turns over and falls with the e^{12t} dependence characteristic of the region $m_\pi^2\leqslant|t|\leqslant 0.2$. It is worth noting that when plotted in this way the results of the DESY bubble chamber are consistent with our data down to a photon energy of 1.4 GeV. We have fitted all the data from $t_{\rm min}$ to m_π^2 to the form

$$(s-M^2)^2\frac{d\sigma}{dt}=\frac{a+bt+ct^2}{(|t|+m_\pi^2)^2} \tag{7}$$

in order to extrapolate the cross section to $t=0$. Equation (7) gives the t dependence to be expected from OPE plus a slowly varying background. We find

$$(s-M^2)^2(d\sigma/dt)(t=0)=350\pm 120\ \mu\text{b GeV}^2. \tag{8}$$

The solid curve in Fig. 1(c) shows the cross section expected in a minimal, gauge-invariant extension of OPE.[10] This model agrees quite well with the data at very small momentum transfers and it is interesting to note that the cross

Table I. Differential cross sections for $\gamma p\to\pi^-\Delta^{++}$.

5 GeV		8 GeV		11 GeV		16 GeV	
$-t_{\rm min}=0.00148$ GeV^2		$-t_{\rm min}=0.00090$ GeV^2		$-t_{\rm min}=0.00063$ GeV^2		$-t_{\rm min}=0.00043$ GeV^2	
$-t$ GeV^2	$\frac{d\sigma}{dt}$ μb/GeV^2	$-t$ GeV^2	$\frac{d\sigma}{dt}$ μb/GeV^2	$-t$ GeV^2	$\frac{d\sigma}{dt}$ μb/GeV^2	$-t$ GeV^2	$\frac{d\sigma}{dt}$ μb/GeV^2
0.0017	< 12	0.00106	2.18 ± 0.75	0.00093	1.81 ± 0.27	0.00097	0.596 ± 0.089
0.0050	10.2 ± 1.5	0.00145	2.94 ± 0.79	0.00164	1.30 ± 0.20	0.00261	0.809 ± 0.122
0.0101	10.9 ± 1.6	0.00351	3.62 ± 0.58	0.00380	2.70 ± 0.40	0.00971	0.982 ± 0.133
0.0201	10.7 ± 1.6	0.00431	4.31 ± 0.65	0.00582	2.54 ± 0.38	0.0134	1.16 ± 0.17
0.0399	7.90 ± 1.2	0.00521	4.26 ± 0.68	0.00836	2.18 ± 0.33	0.0176	1.05 ± 0.16
0.0701	5.77 ± 0.86	0.00620	4.51 ± 0.68	0.0114	1.83 ± 0.27	0.0212	0.900 ± 0.135
0.150	2.64 ± 0.40	0.0101	4.33 ± 0.65	0.0201	2.10 ± 0.31	0.0396	0.682 ± 0.102
0.250	1.14 ± 0.17	0.0198	4.33 ± 0.65	0.0400	1.69 ± 0.25	0.0694	0.486 ± 0.073
0.400	0.478 ± 0.072	0.0376	3.71 ± 0.56	0.0705	1.19 ± 0.18	0.0991	0.326 ± 0.049
0.600	0.280 ± 0.042	0.0688	2.14 ± 0.32	0.150	0.459 ± 0.069	0.149	0.182 ± 0.027
		0.152	1.05 ± 0.16	0.249	0.226 ± 0.033	0.249	0.0968 ± 0.0150
		0.246	0.479 ± 0.072	0.400	0.107 ± 0.016	0.399	0.0657 ± 0.0100
		0.401	0.237 ± 0.036	0.601	0.0812 ± 0.0122	0.597	0.0472 ± 0.0072
		0.602	0.113 ± 0.017	1.00	0.0351 ± 0.0053	0.796	0.0283 ± 0.0042
		0.801	0.104 ± 0.016			0.999	0.0170 ± 0.0025
		1.035	0.068 ± 0.010			1.50	0.00255 ± 0.00038
						2.00	0.00035 ± 0.00009

sections for $\gamma p\to\pi^+n$, $\gamma n\to\pi^-p$, and $\gamma p\to\pi^-\Delta^{++}$ are all reproduced to within 20% by minimal, gauge-invariant OPE over the range 5-16 GeV and $|t|\lesssim 2m_\pi^2$. At larger momentum transfers the model predicts more cross section than observed.

The total cross section for Δ^{++} photoproduction can be obtained by integrating the forward differential cross section; the contributions from the big-t and -u regions are expected to be a few percent or less. The results of this experiment give

$$\sigma(\gamma p\to\pi^-\Delta^{++})=33\ \mu\text{b}/k^2 \tag{9}$$

(for the laboratory photon energy k in GeV) with a systematic uncertainty of ±20%. This parametrization also fits the bubble-chamber data,[2] down to $k=1.2$ GeV, below which there is a 50% increase near $k=1$ GeV and then a rapid falloff to threshold.

The vector-dominance model has been successfully used to relate single-$\pi^\pm$ photoproduction to ρ^0 production by pions.[11] A similar relation can be obtained for Δ^{++} photoproduction if one assumes that

$$A(\pi^+p\to V^0\Delta^{++})=A(V^0p\to\pi^-\Delta^{++}). \tag{10}$$

Note that this assumption cannot be obtained merely by invoking time-reversal and isospin invariance as was possible for the single-$\pi^\pm$ photoproduction relation, but requires in addition s-u crossing symmetry. With the above assumption the vector-dominance model predicts

$$d\sigma(\gamma p\to\pi^-\Delta^{++})/dt=|A_\rho+A_\omega+A_\varphi|, \tag{11}$$

where

$$|A_V|^2=g_{V_\gamma}[\rho_{11}{}^{\text{hel}}d\sigma/dt]_{\pi^+p\to V^0\Delta^{++}}.$$

The ρ contribution is expected to be dominant, and although $\pi^+p\to\rho^0\Delta^{++}$ has been studied at low energies as well,[12] we will concentrate on the 8-GeV/c data of the Aachen-Berlin-CERN collaboration.[13,14] They have obtained the ρ-helicity density matrix by fitting the ρ decay angular distributions (of events with $0.66\le M_{\pi^+\pi^-}\le 0.86$ GeV and $1.12<M_{p\pi^+}\le 1.32$ GeV) directly in the helicity frame. Their $\rho_{11}{}^{\text{hel}}$ values are shown in the inset of Fig. 2 together with the values from lower energy experiments (obtained by rotating the density matrix from the Jackson to the helicity frame).

Using $g_{\rho\gamma}{}^2=(3.5\pm0.5)\times10^{-3}$,[15] the ρ-dominance prediction calculated from the bubble-chamber data is smaller than that from the experimental data by roughly a factor of 3, as shown in Fig. 2. To calculate the extreme limits of the vector-dominance model we have assumed complete constructive (destructive) interference of the A_ω and A_ρ amplitudes, and in addition, allowance for the uncertainty in the various quantities was made by adding (subtracting) 1 standard deviation, as calculated by adding the individual uncertainties in quadrature. The ω differential cross section used was taken from Ref. 13, $g_{\omega\gamma}{}^2=(0.39\pm0.08)\times10^{-3}$ was taken from Ref. 15, and $\rho_{11}{}^\omega=0.35\pm0.07$ was obtained by rotating the Jackson density matrix obtained by the Aachen-Berlin-CERN collaboration to the helicity frame. As can be seen from Fig. 2, the prediction and the data are just compatible for $|t|\gtrsim 0.2$ GeV^2 under the extreme assumption of complete constructive interference plus a 1-standard-deviation shift in the parameters used to make the prediction. At $|t|\lesssim 0.1$ GeV^2 there remains a factor of 2 discrepancy. Given the success of the vector-dominance model for the single-pion differential cross section, we tend to ascribe the Δ^{++} discrepancy to the assumption made in Eq. (10). This assumption is valid in general only for a single t-channel exchange and may not be valid if several t-channel exchanges are important or if factorization does not work.[13]

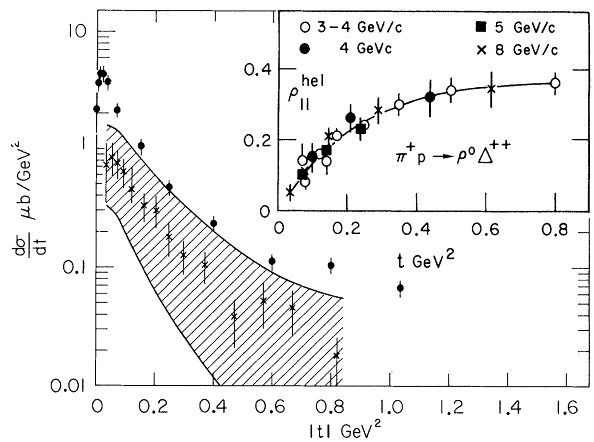

FIG. 2. Comparison of photoproduction of $\pi^-\Delta^{++}$ and pion production of $\rho^0\Delta^{++}$ and $\omega^0\Delta^{++}$ by means of the vector-dominance model. The crosses represent the ρ^0 contribution. The boundaries of the crosshatched region give the limits of the ρ-plus-ω contribution assuming maximum ρ-ω interference and including the statistical plus systematic errors added in quadrature. The solid points are the results of this experiment at 8 GeV. The insert shows ρ_{11} (helicity) used to determine the $\rho\Delta^{++}$ contribution.

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[9]At 5 GeV the $\Delta+\rho$ fits gave 15 to 35% less Δ cross section than did the Δ+Drell fits; at 8 GeV this difference was $\lesssim 15\%$.

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EXPERIMENTAL TESTS OF THE QUARK MODEL USING THE REACTION $K^-p \to \bar{K}^*\Delta$ AT 2.6 GeV/c *

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Predictions of the quark model of high-energy scattering are tested by using the reaction $K^-p \to \bar{K}^*\Delta$. All predictions are satisfied when interpreted as applying in the t-channel coordinate system.

The joint decay angular distribution in $K^-p \to K^*\Delta$ is used to test predictions derived from the quark model of high-energy scattering by Bialas and Zalewski.[1] These authors have assumed the additivity of the quark-quark scattering amplitudes, and have classified their predictions into three groups, each progressively more restrictive in additional assumptions concerning equalities among certain quark-quark spin-flip amplitudes.

We find the data in excellent agreement with the predictions of the first two classes. For the third class the coordinate system in which the predictions are expected to hold is not specified by the model. We find the data in satisfactory agreement with these predictions in the t-channel coordinate system[2] but not in the helicity coordinate system.[3]